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Enhancing Active Transportation and Demand Management (ATDM) with Advanced and Emerging Technologies and Data Sources

NOTICE

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16. Abstract

The purpose of this document is to provide information for enhancing Active Transportation and Demand Management (ATDM) applications using emerging technologies and data sources. It discusses the emerging technologies and data sources, along with ATDM applications. It provides organizational information and operations and maintenance information for future deployments. Design and deployment elements and methods are discussed. Included are challenges that are encountered as well as case studies.

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LIST OF ACRONYMS

ACC	Adaptive cruise control
ADM	Active demand management
AI	Artificial intelligence
AID	Automatic incident detection
AMS	Analysis, modeling, and simulation
APC	Automatic passenger counters
APM	Active parking management
ATDM	Active transportation and demand management
ATM	Active traffic management
ATMS	Advanced transportation management system
AV	Autonomous vehicle
AVL	Automatic vehicle location
BI	Buffer index
BSM	Basic safety message
CAD	Computer aided dispatch
CAPRI	Congestion and parking relief incentives
CAV	Connected and autonomous vehicle
CCP	Connected citizen program
CCTV	Closed circuit television
CIP	Continuous improvement process
ConOps	Concept of operations
COP	Common operating picture
DL	Deep learning
DMA	Dynamic mobility application
DMS	Dynamic message sign
DOT	Department of Transportation
DSRC	Dedicated short range communications
DSS	Decision support system
ETL	Extract, transform, load
FAST	Fixing America's Surface Transportation Act
FAVES	Fleets of autonomous vehicles that are electric and shared
FHWA	Federal Highway Administration
FIPS	Federal information processing standard
GID	Geometric intersection description
GIS	Geographic information system
GPS	Global positioning system
HD	High definition

LIST OF ACRONYMS (CONTINUED)

HOT	High occupancy toll
HOV	High occupancy vehicle
I-	Interstate
ICM	Integrated corridor management
ICMS	Integrated corridor management system
IMO	Integrating mobile operations
IMU	Inertial measurement unit
IAC	Infrastructure as code
IoT	Internet of things
IT	Information technology
ITS	Intelligent transportation system
JPO	Joint Program Office
LCS	Lane control system
LDM	Logical data management
LiDAR	Light detection and ranging
MAW	Motorist advisory warning
M&O	Management and operations
ML	Machine learning
MOE	Measure of effectiveness
MPO	Metropolitan Planning Organization
O&M	Operations and maintenance
OD	Origin destination
PB	Petabyte
PCP	Pre-commercial procurement
PDM	Probe data message
PDM	Physical data management
PII	Personally identifiable information
PMT	Person miles traveled
PTI	Planning time index
RFID	Radio frequency identification
ROI	Return on investment
RWIS	Road weather information system
SANDAG	San Diego Association of Governments
SMART	Specific, measurable, attainable, realistic, and time bound
SPAT	Signal phasing and timing
SR	State route
STIP	Statewide transportation improvement program

LIST OF ACRONYMS (CONTINUED)

TB	Terabyte
TIPS	Transportation improvement programs
TMC	Traffic management center
TM CMF	Traffic management capability maturity framework
TM CMM	Traffic management organizational capability maturity model
TRB	Transportation Research Board
TSMO	Transportation systems management and operations
TIRTL	Infrared traffic logger
USDOT	U.S. Department of Transportation
UAV	Unmanned aerial vehicles
V2I	Vehicle to infrastructure
V2P	Vehicle to pedestrian
V2V	Vehicle to vehicle
V2X	Vehicle to others
VCTMC	Virtual corridor transportation management center
VDT	Vehicle data translator
VIPS	Video image processing system
VMS	Variable message sign
VMT	Vehicle miles traveled
VSL	Variable speed limit
WRTM	Weather responsive traffic management

EXECUTIVE SUMMARY

Per the Federal Highway Administration (FHWA) Office of Operations, active transportation and demand management (ATDM) is defined as:

> "….the dynamic management, control, and influence of travel demand, traffic demand, and traffic flow on transportation facilities. Through the use of available tools and assets, traffic flow is managed, and traveler behavior is influenced in real time to achieve operational objectives, such as preventing or delaying breakdown conditions, improving safety, reducing emissions, or maximizing system efficiency." (5)

ATDM solutions aim to leverage data sources and technologies to manage capacity and demand on facilities to reduce congestion and delay; respond to incidents and provide traveler information based on real-time data; and balance resources across active traffic management (ATM), active demand management (ADM), and active parking management (APM) for optimal solutions.

This document informs agencies of the technology and data sources available to modify and enhance their ATDM solutions from static/responsive management to truly proactive management. To identify emerging technologies and data sources, a detailed literature review was conducted. In addition, interviews with public agencies and private companies that implement ATDM solutions were conducted to determine what technologies and data sources are in use today. Listed below are the emerging technologies and data sources that are relative to the next-generation ATDM concepts and solutions.

Sample list of emerging technologies:

Data technologies:

- Light detection and ranging (LiDAR).
- Laser.
- Automatic vehicle location (AVL).
- Global positioning system (GPS)/ phone-based probe data.
- Crowdsourced data.
- Internet of things (IoT).
- Cloud computing.
- Big data technologies.
- Block chain.
- Data analytics.
- Commercial transactional data.

Vehicle technologies:

- Connected vehicle.
- Autonomous vehicle (AV).

Sensor technologies:

- Video analytics sensors.
- Air quality monitoring sensors.
- Smart lighting.
- Gunshot detectors.
- Bluetooth/WiFi sensors.

Decision support system technologies:

- Artificial intelligence (AI).
- Machine learning (ML).
- Deep learning (DL).
- Cloud computing.
- Edge computing.
- Voice drive assistants.
- Data analytics.

Sample list of emerging data sources:

Connected travelers data:

- Crowd sourced data (e.g., speed, incident, event, and congestion data).
- Connected citizen applications.
- Crowd sourced video.

Connected vehicle data:

- Basic safety messages (BSM).
- Probe data messages.
- Others.

Connected infrastructure data:

- Roadside dedicated short range communication (DSRC)/BSM collection.
- High-definition (HD) signal data.
- ATM and intelligent transportation system (ITS) devices, e.g., signals, signs, cameras, road weather information system (RWIS), etc.
- IoT.

Map technologies:

- Crowdsourced mapping data.
- High resolution map data (LiDAR or similar) and other asset management systems.
- Real-time trajectory data.

Other data sources:

- Real-time turning movement data.
- Bluetooth re-identification.
- Mobile sensors.
- HD maps.

The literature search and interviews also provided information on what ATDM concepts agencies have planned for the future. ATDM implementations go through the same steps:

- Monitor the system.
- Assess system performance.
- Evaluate and recommend dynamic actions.
- Implement dynamic actions.

By incorporating the emerging technologies and data sources at each step, ATDM implementation will be improved. Use cases provide examples of how ATDM is accomplished now and what can be enhanced using new technologies and data sources.

Planning for ATDM implementation is a complex process and involves advanced planning. This report provides information for planning an ATDM implementation:

- **Organizational Capability** - discusses the organizational capability concepts that support successful ATDM operations.
- **Planning for Modified ATDM Operations** - discusses specific efforts that an agency undertakes to plan for operations, including scenario planning and use of data.

- **Setting Objectives and Performance Measures** - describes the importance of identifying objectives and performance measures for operations.
- **Analysis, Modeling, and Simulation** - discusses the types of analyses that are useful in assessing the feasibility and potential impacts of ATDM solutions on specific corridors.
- **Programming and Budgeting** - describes strategies for programming and budgeting for ATDM solutions on a regional basis.

For the planning to be successful, design and deployment elements need to be considered. Data management, system platforms, and infrastructure need to be considered. Technology testing and public outreach are also important considerations. Operations and maintenance (O&M) are also an integral component in planning for ATDM enhancements. It is necessary to consider such items as cybersecurity, performance monitoring, costs, and future proofing.

This document concludes with several case studies that exemplify the use of ATDM solutions in conjunction with emerging technologies and data sources.

CHAPTER 1. INTRODUCTION

Per the Federal Highway Administration (FHWA) Office of Operations, active transportation and demand management (ATDM) is defined as:

> "….the dynamic management, control, and influence of travel demand, traffic demand, and traffic flow on transportation facilities. Through the use of available tools and assets, traffic flow is managed, and traveler behavior is influenced in real time to achieve operational objectives, such as preventing or delaying breakdown conditions, improving safety, reducing emissions, or maximizing system efficiency." (5)

ATDM solutions aim to leverage data sources and technologies to manage capacity and demand on facilities to reduce congestion and delay; respond to incidents and provide traveler information based on real-time data; and balance resources across active traffic management (ATM), active demand management (ADM), and active parking management (APM) for optimal solutions.

ATDM concepts and the vision of Transportation Systems Management and Operations (TSMO) have been around since the beginning of intelligent transportation system (ITS) deployments. Figure 1 is a picture of the Lodge Freeway from the early 1960s. It has similar elements/strategies as a modern-day ATM system (e.g., variable speed limits (VSLs), dynamic lane use control, and ramp metering), but newer technologies and data sources were used to deploy these same types of solutions over time and they will continue into the future. These technological changes make the vision possible in ways we could only dream of in the past. It is important to be aware of technologies and data sources available today, be cognizant of what is coming next, and start planning for it now. This document is about how new technologies and data sources can improve the way we implement ATDM concepts and solutions that we will be using for the foreseeable future.

Source: FHWA

Figure 1. Photograph. The Lodge Freeway (Michigan).

Figure 2 represents another example of an ATM implementation with the implementation of VSLs, dynamic lane management, and dynamic shoulder use. This system uses a more modern technology to help implement dynamic shoulder use. Video analytics cameras are used to monitor the shoulder and determine if there are any stopped vehicles in the shoulder before the ATM solution is put into effect. In older dynamic shoulder use implementations, manual methods (i.e., service patrol vehicles manually drive the shoulder length to verify it as clear) were used before activating the 'should use' signs. Now using more modern technologies, along with this manual, an expensive and time-consuming method can be eliminated.

Source: VDOT

Figure 2. Photograph. Interstate-66 advanced traffic management including dynamic shoulder use.

1.1 Document Purpose

This document informs agencies of the technology and data sources available to modify and enhance their ATDM solutions from static/responsive management to truly proactive management. Viable emerging technologies and data sources will be described, and information will be provided on how advanced and emerging technologies and data sources can enhance specific ATDM approaches and solutions under ATM, ADM, and APM. It should be noted that technologies change quickly, and the information contained in this Reference represents a snapshot in time. Much of the information in this document will be relevant to agencies applying new technology in the future but there may be additional technologies and data sources to be investigated as well.

This document will discuss the steps of the active management cycle (i.e., monitor the system, assess system performance, evaluate and recommend dynamic actions, and implement dynamic actions) and how these steps can be enhanced with new technology and data sources. Also, information is provided as it relates to design considerations, operations and maintenance (O&M) considerations, as well as challenges and pitfalls.

1.2 Objectives

The objectives of this document are as follows:

- Educate current and future implementers of ATDM concepts and solutions about new technologies and data sources that are available to help enhance their deployments.
- Increase awareness about the linkages and synergies between ATDM and advanced and emerging technologies and data sources.
- Investigate the potential impacts, opportunities, efficiencies, and challenges of leveraging advanced and emerging technologies and data sources to enhance ATDM deployments.
- Investigate how agencies can prepare for deploying and operating ATDM in a fast-changing world of technology.
- Advance improvements to existing ATDM operations and deployments and to see deployments of new ATDM solutions that use the latest technologies and data sources.

1.3 Target Audience

The target audience for this ATDM Reference include:

- Agencies and companies that currently deploy ATDM solutions and wish to understand how they can be enhanced.
- Engineering consultants, technology companies, systems integrators, ATDM software solution providers, and ITS equipment providers who can shape products, projects, and systems to ATDM.
- Legislative, executive, and policy staff who need to understand ATDM.
- City, County, and State transportation planners, system managers, and project development professionals who seek to identify and evaluate potential ATDM approaches in planning and development.
- City, County, and State project engineers, ATDM infrastructure designers, finance specialists, agency procurement departments, and legal professionals who need to plan, implement, and operate within the ATDM paradigm.

1.4 Document Organization

The document organization follows this structure:

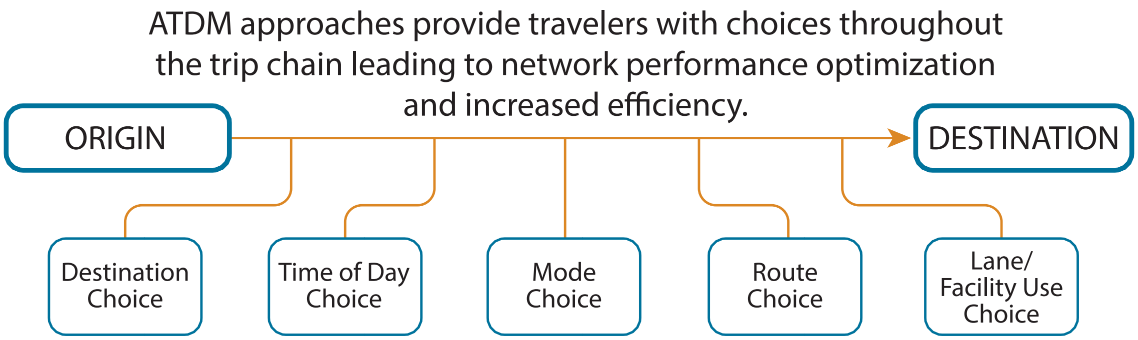
- Chapter 1 – Introduction.
- Chapter 2 – Emerging Technologies and Data Sources.
- Chapter 3 – ATDM Applications.
- Chapter 4 – Planning and Organizational Considerations.
- Chapter 5 – Design and Deployment Elements and Methods.
- Chapter 6 – O&M Considerations.
- Chapter 7 – Case Studies.
- Appendix A – References.

1.5 Active Transportation and Demand Management Overview

ATDM is not simply a system deployment of hardware but rather an operational philosophy or concept. At ATDM's core is *active management* of the system and of demand. The culture of an actively managed operations includes:

- Focus on now.
- Recognition that conditions vary.
- Orientation towards customers and their service needs.
- Focus on performance.
- Emphasis on management of system rather than development of system.
- Operation runs 24/7, not just 9 to 5.
- Scaled to trip – not just a jurisdiction.

The ultimate vision of ATDM is to dynamically manage all components and aspects across the trip chain, as is illustrated in figure 3, by providing travelers with choices (e.g., destination choice, time of day choice, mode choice, route choice and lane/facility choice).



Source: FHWA[29]

Figure 3. Illustration. Dynamic management across the entire trip chain.

- **Destination Choice –** Decision on whether to make the trip and where to go. Traditionally, this is a long-term choice, but day-to-day or even hour-to-hour impacts are possible.
- **Time of Day Choice –** Decision on when a trip is to be made. Real-time traveler information, for example, can affect this choice on a direct hour-to-hour basis.
- **Mode Choice –** Decision on how trip is to be made, including decision to drive alone, carpool, use a form of public transport, or some other form of rideshare (e.g., slug lines). Dynamic information such as comparative travel times, real-time arrivals/schedule disruption/event/incident information, etc., play a role in choice scenarios.
- **Route Choice –** Decision on what road or transit route is to be taken, based on the most direct, fastest, or most cost-effective option.
- **Lane/Facility Use Choice –** This decision is influenced by current operational conditions on the travel route and may involve options related to higher cost/better level of service in comparison with normal costs and normal/substandard level of service, including toll lanes/high occupancy toll (HOT) lanes.

ATDM is divided into three approaches used to improve trip reliability, safety, and throughput of the surface transportation system: [18, 19, 20, 21, and 50.]

ATM:

- A suite of solutions that actively manage traffic on a facility.
- Dynamically manages recurrent and non-recurrent congestion based on prevailing and predicted traffic conditions.
- Current examples of ATM include dynamic lane use, dynamic speed limits, queue warning, dynamic shoulder use, adaptive ramp metering, and others.

ADM:

- A suite of solutions intended to reduce or redistribute travel demand to alternate modes or routes that incentivizes drivers by providing rewards for traveling during off-peak hours with less traffic congestion.
- Dynamically manages demand, which could include redistributing travel to less congested times or routes or by influencing mode choice.
- Current examples of ADM include dynamic ridesharing, on-demand transit, dynamic pricing, and predictive traveler information.

APM:

- A suite of solutions designed to effect the demand on parking capacity.
- Dynamically manages parking facilities in the region to optimize utilization while influencing travel behavior.
- Current examples of APM include dynamically priced parking, dynamic parking reservation, dynamic wayfinding, and dynamic parking capacity.

ACTIVE MANAGEMENT CYCLE

Using the active management cycle, the transportation system is continuously monitored, with actions being performed in real-time to maximize system efficiency. A diagram of the active management cycle is shown in figure 4.

Source: FHWA

Figure 4. Illustration. Active management cycle. [1]

Monitor System – Through interfaces with sensors, data feeds, and other technologies, the system is continually monitored and, in most cases, these data are stored for future analysis and processes.

Assess System Performance – Using data related to prevailing and predictive traffic conditions (i.e., the "monitoring" data), the system is continuously assessed for current and expected system performance.

Evaluate and Recommend Dynamic Actions – Using assessed system performance data and considering all potential ATDM approaches, the system will evaluate potential dynamic actions to take (e.g., control a traffic signal or dynamic message sign [DMS]) and recommend which actions are most suitable to implement.

Implement Dynamic Actions – The recommended system actions are then "activated" putting them into live operation.

ACTIVE TRAFFIC MANAGEMENT

How Active Traffic Management manages recurrent and non-recurrent congestion

ATM manages recurrent and non-recurrent congestion using prevailing and predicted traffic conditions to manage lane/facility operations with direct interaction with the driver encouraging them to make tactical decisions.[(6)]

Description of Active Traffic Management approach

ATM is the ability to dynamically manage recurrent and non-recurrent congestion based on prevailing and predicted traffic conditions. Focusing on trip reliability, it maximizes the effectiveness and efficiency of the facility. It increases throughput and safety through the use of integrated systems with new technology, including the automation of dynamic deployment to optimize performance quickly and without delay that occurs when operators must deploy operational strategies manually. ATM approaches focus on influencing travel behavior with respect to lane/facility choices and operations. ATM solutions can be deployed singularly to address a specific need (i.e., utilizing adaptive ramp metering to control traffic flow) or can be combined to meet system-wide needs of congestion management, traveler information, and safety, resulting in synergistic performance gains.

ATM dynamically manages recurrent and non-recurrent congestion based on prevailing and predicted traffic conditions. Recurrent congestion occurs when demand increases beyond the available capacity. Non-recurrent congestion results from a decrease in capacity, while the demand remains the same. This kind of congestion usually results when one or more lanes are temporarily blocked from events such as crashes, disabled vehicles, work zones, adverse weather events, and planned special events. ATM expects changing conditions by evaluating current or prevailing traffic conditions based on real-time sensor data, as well as predicted traffic conditions based on archived data fused with demand modeling.

The primary classes of actions taken by ATM solutions are active management of capacity and the direct interaction with the driver to encourage them to make tactical decisions in vehicle or driver performance.

Strategies

An agency can deploy a single ATM approach to capitalize on a specific benefit or can deploy multiple active strategies to gain other benefits across the entire transportation system. Some example approaches are included in table 1.

Table 1. Active traffic management solutions.

Strategy	Description
Adaptive Ramp Metering	Use of traffic signals on ramps to control the rate a vehicle enters a freeway facility, thus allowing efficient use of freeway capacity.
Adaptive Traffic Signal Control	Continuously monitor arterial traffic conditions and queuing and optimize one or more operational objectives.
Dynamic Junction Control	Dynamically allocating lane access on mainline and ramp lanes in interchange areas.
Dynamic Lane Reversal or Contraflow Lane Reversal	Reversal of lanes to dynamically allocate the capacity of congested roads based on prevailing or predictive conditions.
Dynamic Lane Use Control	Dynamically open/close traffic lanes as needed and provide travelers advance warning.
Dynamic Merge Control	Dynamically managing entry of vehicles into merge areas with messages approaching merge point, preparing motorists for an upcoming merge and encouraging or directing a merging behavior.
Dynamic Shoulder Lanes or Part-Time Shoulder Use	Enables use of shoulder as a travel lane(s) based on congestion levels.
Dynamic Speed Limits	Adjust speed limits based on real-time traffic, roadway, and/or weather conditions.
Queue Warning	Provide real-time warning messages to alert travelers that slowdowns are ahead.
Traffic Signal Priority	Manage traffic signals by using sensors or probe vehicle technology to detect when a bus nears a signal-controlled intersection.

ACTIVE DEMAND MANAGEMENT

How Active Demand Management 'redistributes' travel

ADM redistributes travel by focusing on influencing travel behavior of the traveling public with incentives and disincentives by presenting choices in mode, time, route, or location of travel.[7]

Description of Active Demand Management approach

ADM uses information and technology to dynamically manage traffic demand. One key tenet of ATDM is the ability to influence travel behavior in real-time. This is consistent with the desire to maximize available choices of mode, time, route, or location of travel. Traditional demand management focuses on mode choice, but ADM goes a step further to use information and technology that could redistribute travel to less congested times of day or routes.

Incentives or disincentives, sometimes called financial levers, are important components of ADM. The specific list of financial levers varies by target, but could take the forms of:

- Travel time discounts or assessments.
- Direct financial incentives for avoiding peak-hour travel.
- Gift certificates through points accumulated by offering rides with dynamic ridesharing vendors.
- Shopping information or discounts to encourage changes in departure times during peak periods.

With advances in connectivity, ADM can match in-route travelers with others needing a ride or provide comparative travel times for traffic and transit to induce an in-route mode or route shift dynamically even after a trip has begun.

ADM uses information and technology to dynamically manage demand, which could include redistributing travel to less congested times of day or routes or reducing overall vehicle trips by influencing a mode choice.

ADM seeks to influence more fluid, daily travel choices to support more traditional, regular mode choice changes. ADM is very supportive of other active measures by redistributing or reducing overall traffic levels during congested conditions, thus becoming an integral part of an overall management philosophy to actively manage a facility or system.

Strategies

An agency can deploy a single ATDM approach to capitalize on a specific benefit or can deploy multiple active strategies to gain other benefits across the entire transportation system. Some example approaches are included in table 2.

Table 2. Active demand management solutions.

Strategy	Description
Dynamic Fare Reduction	Reducing transit system fares in a particular corridor.
Dynamic High-Occupancy Vehicle (HOV) / Managed Lanes	Changing of qualifications for driving in HOV lanes.
Dynamic Pricing	Dynamically changing toll rates based on changing congestion levels.
Dynamic Ridesharing	Through advanced technologies, such as smartphones and social networks, travelers are able to arrange short-notice, one-time shared rides.
Dynamic Routing	Uses variable destination messaging to disseminate information to make better use of roadway capacity.

Table 2. Active demand management solutions. (Continued)

Strategy	Description
Dynamic Transit Capacity Assignment	Reorganizing schedules and adjusting assignments of assets (e.g., buses) based on real-time demand.
On-Demand Transit	Travelers make real-time trip requests for services with flexible routes and schedules.
Predictive Traveler Information	Uses real-time and historical data to predict travel conditions and inform travelers before their departure.
Transfer Connection Protection	Improving reliability of transfers from a high-frequency transit service (e.g., a train) to low-frequency transit services (e.g., a bus).

ACTIVE PARKING MANAGEMENT

How Active Parking Management optimizes utilization of parking facilities

APM provides travelers with real-time parking information. This information helps to maximize utilization of parking resources, and helps travelers make informed choices (e.g., timing, mode, and facility).[8]

Description of Active Parking Management approach

APM is the dynamic management of parking facilities in a region to optimize performance and utilization of those facilities while influencing travel behavior at various stages along the trip-making process: i.e., from origin to destination. Dynamically managing parking can affect travel demand by influencing trip timing choices, mode choice, as well as parking facility choice at the end of the trip. This ATDM approach can also have a positive impact on localized traffic flow by providing real-time parking information to users and ensuring the availability of spaces to reduce circling around parking facilities. The overall goal is to help maximize the nation's transportation infrastructure investments, reduce congestion, and improve safety.

A fundamental component of APM is information. With clear, detailed, relevant, and real-time parking information, travelers can make informed decisions regarding their trip. The information a user needs to make parking-related decisions can be conveyed in numerous ways and in various formats. These include, but are not limited to, traditional static road signs, DMSs, the internet, cell phones, smartphones and similar mobile devices, and navigation systems. Agencies can harness the power of an enhanced technology infrastructure (wireless and wired communications, embedded sensors, etc.) and combine it with the breadth of currently available technologies to convey information as well as to accept reservations and parking payments, monitor use, and conduct enforcement. These technologies can be applied to both on-street and off-street parking spaces to optimize use of all facilities in a region. Parking system operators also realize numerous benefits with APM. Agencies can reduce costs, improve efficiency, and increase parking utilization rates. By increasing the availability of limited parking spaces and optimizing the use of facilities at all times of the day, agencies can help reduce congestion in and around parking facilities, improve enforcement efficiency, foster public trust, and reduce the receipt of parking tickets by accommodating alternative payment methods. APM also helps a region as a whole by reducing pollution, encouraging the use of alternative modes, relieving congestion around commercial businesses, and helping improve access by emergency responders. In some cases, agencies can actually increase parking capacity in a limited footprint with innovative parking facility designs that stack vehicles and/or automate parking.

APM dynamically manages parking facilities in a region for optimum use.

Strategies

An agency can deploy a single ATDM approach to capitalize on a specific benefit or can deploy multiple active strategies to gain other benefits across the entire transportation system. Some example approaches are included in table 3.

Table 3. Active parking management solutions.

Strategy	Description
Dynamically Priced Parking	Use of dynamically generated parking fees based on demand and availability.
Dynamic Parking Reservation	Utilizes technology to reserve a parking space on demand to ensure availability.
Dynamic Wayfinding	Provide real-time parking location and availability to reduce time spent searching for parking.
Dynamic Overflow Transit Parking or Dynamic Capacity	Dynamically uses overflow parking near transit stations or park-and-ride facilities when existing parking is at or near capacity.

ACTIVE TRANSPORTATION DEMAND MANAGEMENT BENEFITS

Benefits of Today's Active Transportation and Demand Management

Using today's data sources and technologies, the ATDM benefits include:

- A decrease in primary incidents by alerting drivers to congested conditions and promoting more uniform speeds.
- A decrease in secondary incidents by alerting drivers to the presence of queues or incidents and proactively managing traffic in and around incidents.
- Increased throughput by reducing the delay associated with the number of primary and secondary incident, thus reducing speed differential in traffic flow and reducing the shockwave effects of excessive breaking.
- Increased overall capacity by adding shoulder use during congested periods when it is needed most.
- Overall improvement in speed uniformity during congested periods.
- Increased trip reliability by increasing capacity and throughput and reducing incident delay and improving vehicle throughput.

Benefits of Tomorrow's Active Transportation and Demand Management

By adding the previously discussed emerging data sources and technologies to both existing and future ATDM solutions, the expected benefits of tomorrow's ATDM might include:

- Improvement of situational awareness for incident and event management through video analytics and high-resolution vehicle trajectories. Improved incident response, onsite monitoring, and management.
- Provision for new services for road hazard warnings—higher fidelity location information, more accurate confirmation of hazard types, and more timely warnings.
- New sources for speed warnings, intersection collision avoidance—specific recommendations to different vehicle types based on roadway conditions, and more timely warnings.
- Improved traffic signal timing—better operation in oversaturated conditions, more timely updates to fixed timings, broad-based adaptive controls, reduced reliance on physical sensor devices and maintenance, shift towards in-vehicle data delivery, and performance monitoring of signals with no physical links to Department of Transportation (DOT) communications infrastructure.
- Freeway ramp metering—more accurate and coordinated corridor metering algorithms.
- VSL recommendations and lane use control strategies—more accurate and coordinated responses, shift towards in-vehicle signage reducing needs for infrastructure investments.
- DMS displays—more accurate messaging, shift towards in-vehicle signage for more personalized recommendations, and reduced need for infrastructure investments.
- Work zone implementation—higher safety for workers and drivers, higher resolution maps of work zone geometries, real-time information on new zone locations, and less need to manually update locations.[12]
- Broadcasted and personalized traveler information—higher fidelity information, more accurate and timely information, and personalized recommendations.
- Congestion pricing, road user fees, and tolls—more granular toll rates, more accurate congestion prices, personalized tolls, and road user fees.
- Performance measurement, including weather and emissions monitoring—higher fidelity analysis, more comprehensive coverage of geography, and reduced need for infrastructure investments.
- Asset management and maintenance—reduced need for infrastructure investments and faster detection and response to equipment failures.

Related Efforts

In addition to the research referenced in appendix A, there is some very specific research directly associated with this effort that is worth noting:

- There were three pieces of related research that are connected to this effort.(24, 25, and 26) First, FHWA's "Integrating Emerging Data Sources into Operational Practice" research was the follow-on to two projects that developed information resources on the impacts of connected and autonomous vehicles (CAVs) and technologies. After the "Integrating Emerging Data Sources into Operational Practice" project was completed, FHWA initiated the "Decision Support Systems for the Next Generation of Traffic Management Systems" project, followed by "Framing the Next Generation of Traffic Management Systems." These projects frame many of the emerging data and technology issues at an overview or conceptual level, and even begin to look at the cost and computing needs required to support.
- Another directly related ongoing effort is the Transportation Management Center (TMC) Pooled Fund Study called "Considerations of Current and Emerging Transportation Management Center Data." The goal of this study was to better understand current and emerging data types that can be used to improve TMC operations as well as other operational functions. It was also to learn about business models used for selling third-party data and possible ways for identifying the value of agencies' existing data.

This Reference explores more information related to the use of emerging data for ATDM. The same holds true for the possible consideration and use of technologies—what technologies, why, and to do what—along with how this compares to what people are using now, as well as how someone should compare and assess implications of using different technologies.

CHAPTER 2. EMERGING TECHNOLOGIES AND DATA SOURCES

This chapter describes and categorizes emerging data sources and technologies. The descriptions include information on applicability of each technology or data source, which solutions they help, how they apply to the active management cycle, and discussion on the benefits.

2.1 Identification of Emerging Technologies and Data Sources

The methods used to identify the emerging technologies and data sources that can benefit active transportation and demand management (ATDM) were as follows:

- A detailed literature review was conducted, which included the examination of numerous ATDM and other technology documents. The literature that was reviewed was itemized in the "Enhancing ATDM with Advanced and Emerging Technologies and Data Sources, State of the Practice Technical Memorandum" (January 16, 2019). See appendix A for information on some of this literature.
- Interviews were conducted with various public agencies including State and local transportation departments, metropolitan planning organizations (MPOs), and county transportation departments. In addition, private companies that implement ATDM solutions or provide emerging technologies or data sources were also interviewed. These interviews included information on which technologies and data sources are in use today, which future ones were being explored or implemented, as well which other new ones should be looked into or explored.

2.2 Description of Emerging Technologies and Data Sources

Table 4 lists emerging technologies and data sources that are relevant to next-generation ATDM concepts and solutions. From the data perspective, in the modern transportation systems, travelers, vehicles, and infrastructure are equipped with smart devices and connected with each other, under the framework of internet of things (IoT), to share real-time status data for improved system management. Connected travelers, vehicles, and infrastructure collect, share, and store high-resolution data, which can be used to understand traffic patterns, make accurate estimation and prediction of real-time traffic systems, and develop ATDM solutions.

From the technological perspective, data collection technologies, such as connected and autonomous vehicles (CAVs), advanced sensors, and artificial intelligence (AI), make it possible to collect data that are not otherwise available. Further, the new big data in transportation enable the use of emerging decision-making technologies, such as AI/machine learning (ML) and big data analytics/tools, to generate better ATDM solutions. Other emerging technologies, such as edging computing and block chain technologies, make the system more secure and efficient.

Table 4. Sample list of emerging technologies and data sources.

Emerging Technologies	Emerging Data Sources
Data technologies: • Light detection and ranging (LiDAR). • Laser. • Automatic vehicle location (AVL). • Global positioning system (GPS)/phone-based probe data. • Crowdsourced data. • IoT. • Cloud computing. • Big data technologies. • Block chain. • Data analytics. • Commercial transactional data. **Decision support system technologies:** • AI. o ML. o Deep learning (DL). • Cloud computing. • Edge computing. • Voice driven assistants. • Data analytics. **Vehicle technologies:** • Connected vehicle. • Automated vehicle. **Sensor technologies:** • Video analytics sensors (edge and centralized). • Air quality monitoring sensors. • Smart lighting. • Gunshot detectors. • Bluetooth/WiFi sensors.	**Connected travelers data:** • Crowd sourced data (e.g., speed, incident, event, and congestion data). • Connected citizen applications. • Crowd sourced video. **Connected vehicle data:** • Basic safety messages (BSMs). • Probe data messages. • Others. **Connected infrastructure data:** • Roadside dedicated short range communication (DSRC)/BSM collection. • High-definition (HD) signal data. • Active traffic management (ATM) and intelligent transportation system (ITS) devices, e.g., signals, signs, cameras, road weather information system (RWIS), etc. • IoT. **Map technologies:** • Crowdsourced mapping data. • High resolution map data (LiDAR or similar) and other asset management systems. • Real-time trajectory data. **Other data sources:** • Real-time turning movement data. • Bluetooth re-identification. • Mobile sensors. • HD maps.

The volume, variety, velocity, and veracity of connected traveler, connected vehicle, and connected infrastructure data will call for modern methods of processing and storing the information. Even without the connected vehicles and connected traveler data, most agencies are not utilizing the information they currently collect from infrastructure (particularly traffic signal systems) in meaningful ways because these systems were not designed to take advantage of tools and technologies that did not exist 10 or more years ago. Changes to information technology (IT) infrastructure will need to be made as well to take advantage of new data and technologies.

2.3 Categories for Emerging Data Sources

Several emerging data sources are expected to enhance the state-of-the-practice of traffic and demand management. These sources include connected travelers, connected vehicles, connected infrastructure, and other emerging sources. The following sub-sections describe each category of emerging data and identify some of the key characteristics of each data source and the value for ATDM. Status information from connected vehicles and travelers provide high-resolution anonymous trajectories of user experience on the transportation network. In general, such detailed information has never been available to traffic management agencies before. Connected infrastructure allows traffic management centers (TMCs) to continuously monitor infrastructure condition (e.g., traffic, pavement) to make informed decisions for traffic and demand management.

CONNECTED TRAVELERS

The use of mobile devices, primarily smartphones, has evolved over the years and become applicable in enhancing travel and transportation through ITS. A connected traveler is one that is using a mobile device that generates and transmits status data that could be collected, saved, and used by ITS devices and the corresponding traffic management system, other connected mobile devices, and connected vehicles. The majority of travelers are already connected to a suite of applications and services, e.g., WiFi, GPS data, through a personal device that accurately monitors locations up to a few meters precision. Virtual 3G/4G cellular networks and prevalent open WiFi networks enable travelers to experience uninterrupted connectivity. Approximately 68 percent of American adults currently own a smartphone, and the number is expected to exponentially increase as the years go by.

Mobile applications have been developed to collect information about a user's activities and location to enrich the application itself (e.g., Google Maps, Waze) with content, and to personalize information for the user based on their current location using crowdsourcing. Common transportation features on mobile devices include location sharing transit information, social media, traffic report, geographic information system (GIS) maps, and navigation.

Information obtained and disseminated by connected travelers include travel and trip characteristics such as speed, travel time, incidents, mode, and status. This information can be used by traffic management devices or TMCs to inform surrounding connected travelers about traffic and roadway condition. The data may also provide information on traveler behavior that is now only available via expensive and time-consuming travel surveys. TMCs can use the archived historical data to understand demand patterns under different days (e.g., adverse weather, special events) and this is extremely valuable for the development of demand management strategies.

Past transportation systems management and operations (TSMO) strategies have rarely, if ever, included the use of traveler trip characteristics and behavior, but now, with the availability of rich data, these strategies are being utilized for the purpose of traffic management and are expected to improve in the future. Some present-use cases for connected traveler data in ATM are briefly discussed below:

- **Incident and event management –** By measuring the prevailing travel time for a connected traveler on a certain route, inconsistencies in the origin destination (OD) characteristics can be detected by traffic management professionals. Further, using private roadway information provider's applications such as Waze, travelers can share their observation of the roadway segment with TMCs in regard to incidents like crashes; therefore, leading to improved incident response, on-site monitoring, queue detection, verification, and management.

- **Dynamic message sign (DMS)/Variable Speed Limit (VSL) displays –** DMSs or VSLs are used to provide advisory information for drivers. By giving travel characteristics such as advisory speed for travelers, congestions have been drastically reduced. As travelers exchange congestion data with the TMCs, the speed of vehicles approaching a congested region can be harmonized through DMS/VSL, thereby gradually optimizing the traffic.
- **Work zone implementation –** By communicating the presence of a work zone on the path of travelers, alternative routes are given to drivers, thereby reducing possible traffic congestion on regular routes. This has been recorded to lead to higher safety for workers and drivers, higher resolution maps of work zones geometries, real-time information on new zone locations, and less need to manually update locations.

Connected traveler data are mostly collected by private companies (e.g., Google Maps, Waze, etc.) using the applications they have developed. Travelers allow companies to collect and use information about their trips, while the application provides the user with information (e.g., directions). Similar to the trend in public agencies procuring link-speed data from private providers, it is likely that connected traveler data will be increasingly available from private sources. Sharing data from mobile devices on traveler activities and status can provide more information that agencies can use to improve traffic management in the TMC.

Crowd Sourced Data

Crowdsourced data collection is when data from a large, diverse group of people are assembled using technology. Crowdsourced data collection is continually gaining popularity because it is convenient, inexpensive, relatively quick, and generally precise. It consists of building data sets with the help of a large group of people. One example is crowdsourced mobile phone applications (e.g., Waze) where people can report conditions such as roadway crashes and disabled vehicles, potholes, and debris on the roadway. As several people report the same condition, it becomes increasingly reliable and accurate. There are sources and data suppliers who have developed methods to fill-in missing data to enrich existing knowledge. AI companies seek large data sets to find ways to help draw better and new conclusions based on better and richer data sets. These data can be strategically utilized for ATDM solutions.

Connected Citizen Applications

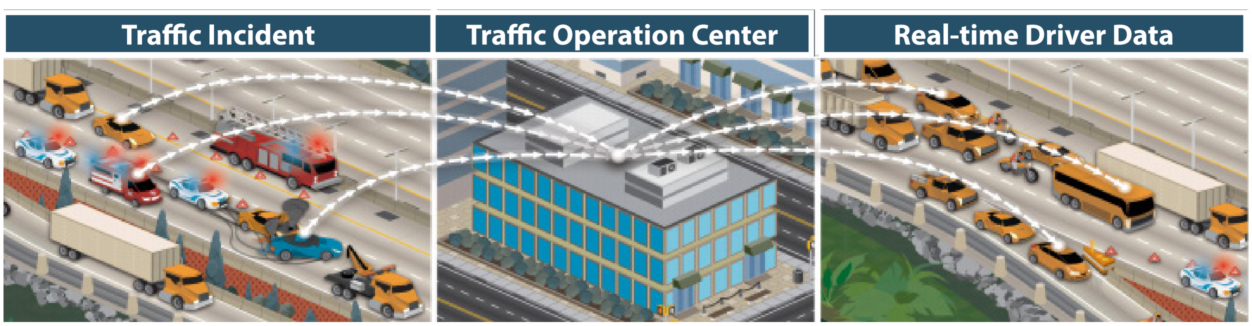
These applications are used to source real-time or near-real-time data for traffic management and control. Travelers can record their observation of roadway and traffic conditions such as congestion, the presence of hazardous materials, work zones activity, or traffic crashes. Waze, for example, is a GPS navigation software application that works on smartphones and tablets that have GPS support, providing navigation, travel times, and route details. Waze introduced the connected citizen program (CCP) building upon data exchange. While Waze can provide rich crowd source data, their map can be significantly enhanced if information such as work zones from public agencies can be included. Via the CCP, hundreds of international cities, departments of transportation (DOTs), and first responders have built meaningful relationships and regularly knowledge share to identify creative solutions.

Crowdsourced Incident and Congestion Data

Connected travelers with smart devices can not only send status data (e.g., speed, location) to TMCs but also report incidents, work zones, and other event data though a user interface of the smart device application. The central server can use special algorithms (e.g., clustering) to infer the most likely information about the incident or event, and then provide it back to the travelers. The data are cost-effective and could reduce the need for more roadside sensors and systems that require installation and maintenance. In addition, it allows agencies to leverage and more effectively use their existing ITS infrastructure. States and local agencies are using crowdsourced data in traffic operations to detect incidents much faster than 911 centers, thus enabling a faster response to the incident.

Crowd-Sourced Video

Users of mobile devices equipped with video recorders or vehicles with video cameras can contribute data to improve traffic management and operations. The use of social media accounts by citizens to upload live videos of events has been useful for security agencies and emergency services. Traffic management media accounts can also source data for event response from social media video uploads of travelers. Typical data exchange through a connected traveler is shown in figure 5.

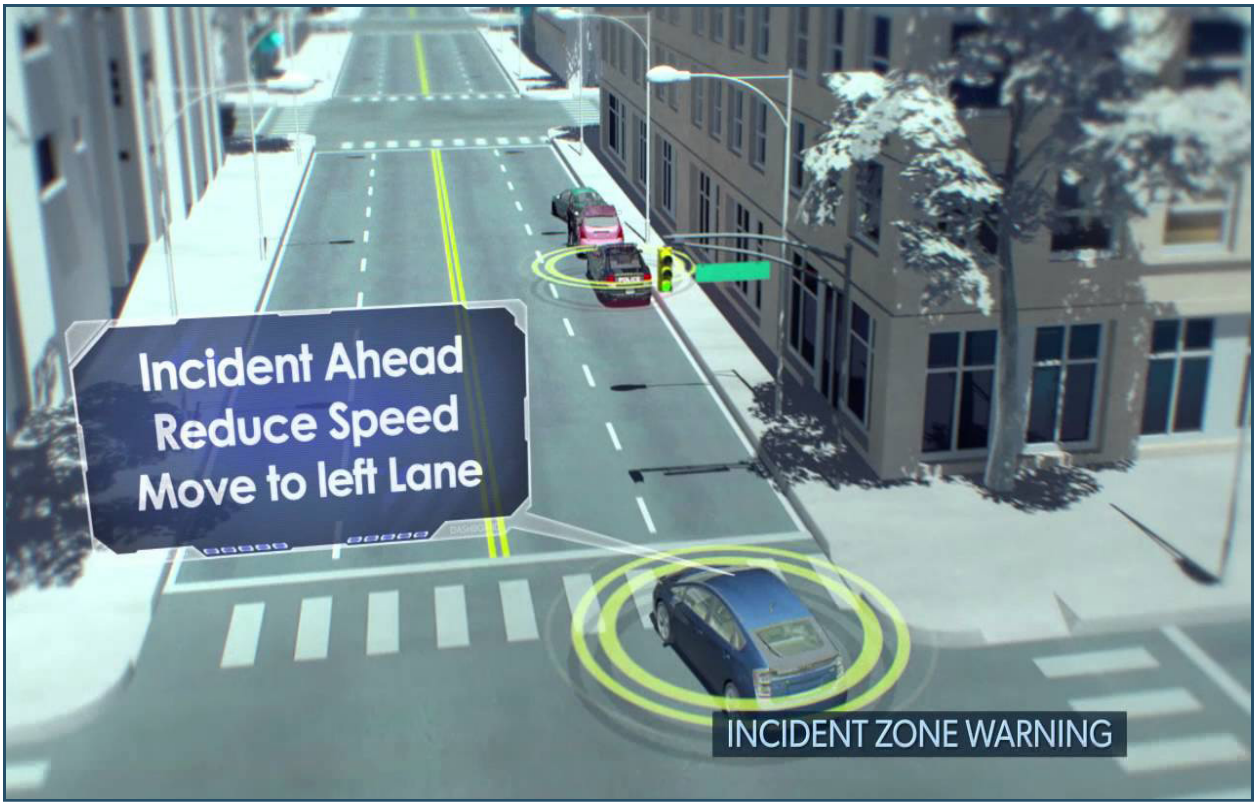


Source: FHWA

Figure 5. Illustration. Connected traveler's data exchange for incident management.

CONNECTED VEHICLES

The concept of connected vehicles refers to the use of wireless communication technologies to establish a communication link between vehicles and/or vehicles and infrastructure. These vehicles communicate their status information directly to other vehicles, road users, and roadside facilities such that every vehicle and element on the road is aware of where other nearby vehicles and traveler are located. The connectivity allows connected vehicles to identify hazards, threats, delays, and incidents, and provide feedback to the TMC for real-time or near-real-time use for traffic control. The TMC can use the collected information from connected vehicles to provide drivers with alerts, warnings, and information on irregular or unusual travel patterns. The key elements of vehicle connectivity include wireless communications, onboard computer processing, advanced vehicle sensors, GPS data, and smart infrastructure. A use case for connected vehicle awareness technology is shown in figure 6. It depicts an approaching connected vehicle receiving a warning message, which can be regarded as BSM, about an incident ahead. A preceding connected vehicle already sent the message to the control center, allowing the oncoming connected vehicle to avoid the effect of the incidence by reducing its speed and moving to another lane.



Source: FHWA

Figure 6. Illustration. Connected vehicle incident zone warning concept.

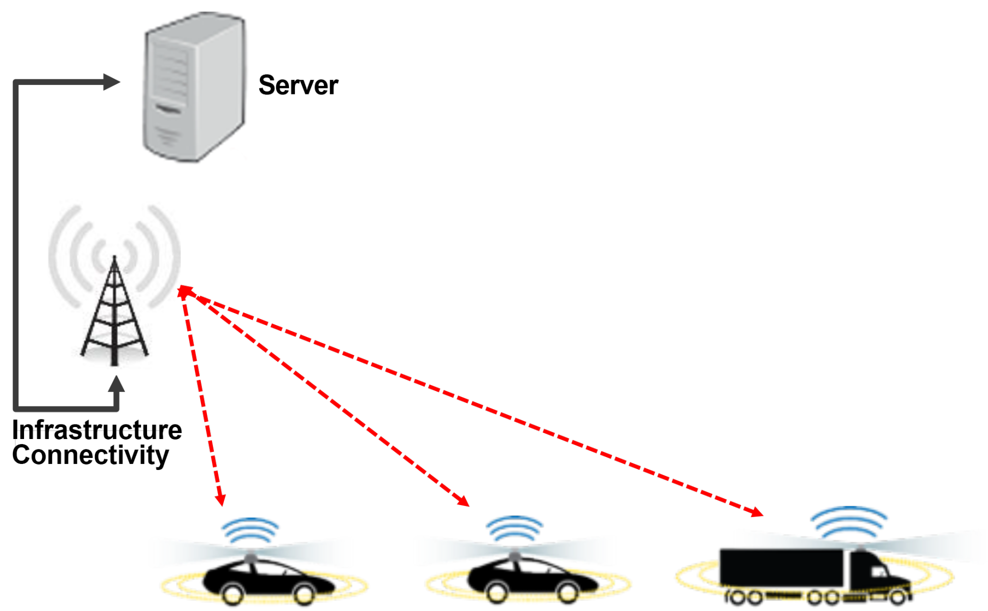
The connectivity of connected vehicles is classified into three types: V2V (vehicle-to-vehicle), V2I (vehicle-to-infrastructure), and V2X (vehicle-to-others, for example, pedestrians and other personal devices). V2V communication enables vehicles to wirelessly exchange information about their speed, location, and heading. This communication technology allows vehicles to broadcast and receive omnidirectional messages (up to 10 times per second), creating a 360-degree awareness of other vehicles in proximity. Vehicles equipped with safety applications can use the messages from surrounding vehicles to determine potential crash threats as they develop. The technology can then employ visual, tactile, and audible alerts or, a combination of these alerts to warn drivers. V2I technologies capture vehicle-generated data, wirelessly providing information such as advisories from the infrastructure to the vehicles that inform the driver of safety, mobility, or environment-related conditions. Enabled by a system of hardware, software, and firmware, V2I communication is typically wireless and bi-directional: infrastructure components such as lane markings, road signs, and traffic lights can wirelessly provide information to the vehicles, and vice versa. V2X allows vehicles to communicate with moving parts of the traffic system around them. Pedestrians, bicyclists, and personal devices are components of V2X interaction, which allow data exchange for storage, processing, and usage in controlling traffic. Connected vehicles may use a variety of communication media for data exchange, including DSRC, cellular, and WiFi. Connected vehicles are divided into three major categories of emerging data sources: Proprietary (commercial) connected vehicle systems; Open connected vehicle systems (U.S. Department of Transportation [USDOT]-sponsored technologies, DSRC); and Radio Frequency Identification (RFID), WiFi, and other technologies.

Commercial connected vehicles include cellular connections to a private cloud from the vehicle's infotainment system or a third-party in-car system for tracking and data collection. Commercial in-vehicle systems are currently primarily used for gaining internet access for a passenger's devices. Other secondary uses are navigation, driver assistance, health monitoring, remote diagnostics, insurance evaluation, road user charging, and automated driving. Several private companies share information related to their commercial fleets with DOTs through aggregation of individual vehicle travel data into summaries of vehicle speeds on roadway links. Real-time link-speed data are currently invaluable to traffic management agencies because it is becoming more challenging for agencies to maintain their spot-speed detection equipment (i.e., in-pavement loop detectors, radar, and video). As of June 2016, HERE has published a voluntary (non-binding) connected vehicle data sharing standard that may accelerate the availability of trajectory-based commercial connected vehicle data to DOTs, assuming the information can be anonymized. To date, eleven major automotive and supplier companies have already joined the SENSORIS Innovation Platform now under the coordination of ERTICO. They are: AISIN AW, Robert Bosch, Continental, Daimler, Elektrobit, HARMAN, HERE, LG Electronics, NavInfo, PIONEER, and TomTom.

On the other hand, open connected vehicle platforms are being developed by USDOT for mobility and safety application. The system relies on DSRC technology to send vehicle status data to other vehicles and infrastructure access points with very low latency. USDOT has supported the development of applications to improve the safety and mobility of connected vehicles.[(64)] Some of these applications are presently being tested at New York, Wyoming, and Florida. These applications rely basically on DSRC to generate and exchange BSM with other vehicles and roadside equipment at high frequency and low latency. In addition to BSMs, a probe data message (PDM) encapsulates a string of "snapshots" (a more comprehensive data element than the BSM) to provide vehicle trajectory information over a longer timeframe than the local trajectories shared by the BSMs. Both messages are shared with Roadside Equipment when the vehicle is within range, although there are alternative transmission methods being considered for transmission of PDMs through cellular communication. In the future, traffic management agencies and TMCs will have the technical ability to process, store, and use BSMs for improving traffic management functions.

CONNECTED INFRASTRUCTURE

The concept of connected infrastructure (figure 7) is based on the emergence of the IoT. IoT refers to the concept of extending connectivity beyond the regular computing platforms such as personal computers and mobile devices, and into a range of non-internet-enabled physical devices and everyday objects. Once upgraded with electronics, internet connectivity, and other forms of hardware such as sensors, these devices can communicate and interact with others over the internet, and they can be remotely monitored and controlled. Connected infrastructure devices include traffic signals, ramp meters, closed circuit television (CCTV), DMS, vehicle detection, RWIS, flood warning, high wind warning, and a variety of other devices. Emerging devices include active traffic management applications of VSLs and lane control system (LCS). Integration and interconnection of corridor management and arterial control and freeway control systems are becoming more common, so also are transit and other demand management systems. For example, signals at intersections can be coordinated to be improved. Traffic preemption and priority is another ATM strategy that has proved effective in emergency management and vehicle-type control. Emergency or fire trucks can send a preemption signal to the intersection traffic light, thereby gaining priority over other approaches. The intersection controller can cut-off an existing signal phase to allow these priority vehicles to leave the intersection by passing the phase unto their approach. Certain vehicle types that can also hinder intersection throughput are equipped with preemption lights, therefore, allowing them to exit the intersection faster, reducing congestion.



Source: FHWA

Figure 7. Illustration. Connected infrastructure architecture.

As data from connected vehicles and travelers provide the same information (at potentially higher resolution), connected infrastructure is still needed because the penetration rate of connected vehicles will not reach 100 percent for more than 20+ years. Currently, most agencies delete or archive old ITS infrastructure status information simply because existing database and processing system technologies are expensive and agencies lack the business case to expand to handle the volume. TMCs can use big data tools and technologies to gain analytical insights if more information from connected infrastructure could be retained and stored. Connected infrastructure can also benefit from the advancement of technologies, such as sensors, AI, and computer vision, to generate more data that are not available in the current systems. For example, connected infrastructure equipped with LiDAR sensors can generate an overall picture of all intersection object movement and, therefore, provide a sound foundation for real-time intersection and traffic signal control. Additionally, conventional video detection can be enhanced with computer vision technologies to generate real-time trajectory information of vehicles and pedestrians, enabling infrastructure to broadcast corresponding safety or mobility messages. While TMCs should be ready for emerging data sources from connected travelers and connected vehicles, empowering connected infrastructure with technologies will be extremely beneficial, particularly in the next decades when the penetration rates of connected travelers and vehicles are still low.

Roadside Dedicated Short Range Communication/Basic Safety Message Collection

DSRC is an open-source protocol for wireless communication. It is intended for highly secure, high-speed wireless communication between vehicles and infrastructure. One of the main advantages is its low latency. The delays involved in opening and closing a connection are very short, on the order of 0.02 seconds, thereby providing real-time or near real-time information exchange within a connection ecosystem. Also, DSRC is very robust in scenarios of radio interference, and its short range (~1000 m) also reduces the chance of interference from distant sources. In adverse conditions, it has been observed to have a strong performance as well. Some of the applications involve transit signal priority and scene management for emergency services. BSM data are also transmitted through DSRC.

High-definition Signal Data

The advancement of sensor technologies, such as video cameras and computer vision, allows the collection of exact vehicle trajectories near the intersection, which can be analyzed along with signal controller data. Additionally, with connected vehicles and infrastructure, traffic signal phasing and timing (SPaT) and intersection geometric MAP messages can be shared in real-time with surrounding vehicles for intelligent signal control.

Active Traffic Management and Intelligent Transportation System Devices

ITS refers to an advanced application that is designed to provide state-of-the-art services relating to different modes of transportation and traffic management. It allows roadway users to make better use of existing infrastructure in a more coordinated and smarter manner. The purpose of ITS technologies is to use communication systems that include wireless radio, Bluetooth and WiFi, microwave systems, and fiber optics to support the operations of highway systems. ITS allows the monitoring and management of roadways from TMCs. Elements of ITS include ATM, traffic cameras (CCTV), variable message signs (VMSs), and RWISs.

OTHER DATA SOURCES

Real-time Turning Movement Data

A variety of sensor technologies, such as loop detectors, traffic cameras, and radar, have been developed for real-time traffic monitoring. Recent advancements make it easier to extract useful data for real-time intersection control such as the adaptive traffic signal control.

Bluetooth Reidentification

Bluetooth reidentification technology has been tested and accepted for over a decade. It provides reidentification through Bluetooth for travel time and OD. This has subsequently been used to improve understanding of driver route choice behavior in the past. The operation mode involves the tracking of Bluetooth signals from vehicles with mobile devices inside them, identifying the signal from a point, and reidentifying the same signal in another point. By comparing the time stamps for identification and reidentification, the travel time, and route choice behavior of drivers can be assessed. This is achieved using two or more Bluetooth identification sensors.

Mobile Sensors

A mobile sensor is defined as a device that records data about the environment where the vehicle is traveling through (rather than data related to the vehicle's status and performance). Mobile sensing enabled by GPS or smartphones has become an increasingly important source of traffic data. Mobile sensors reside in a vehicle and collect data only specific to this vehicle. GPS receivers, acoustic/ultrasonic sensors, and cell phones are examples of mobile sensors. Helicopters, Unmanned Aerial Vehicles (UAVs), and satellites can be categorized as more advanced mobile sensors. For example, UAVs can be flexibly deployed at key locations, such as incident scenes, for traffic monitoring and incident response. Another emerging mobile sensor is LiDAR point cloud and 3D camera data from connected vehicles. These data are collected to support automated vehicle operation, but could be valuable to traffic management functions, particularly incident management.

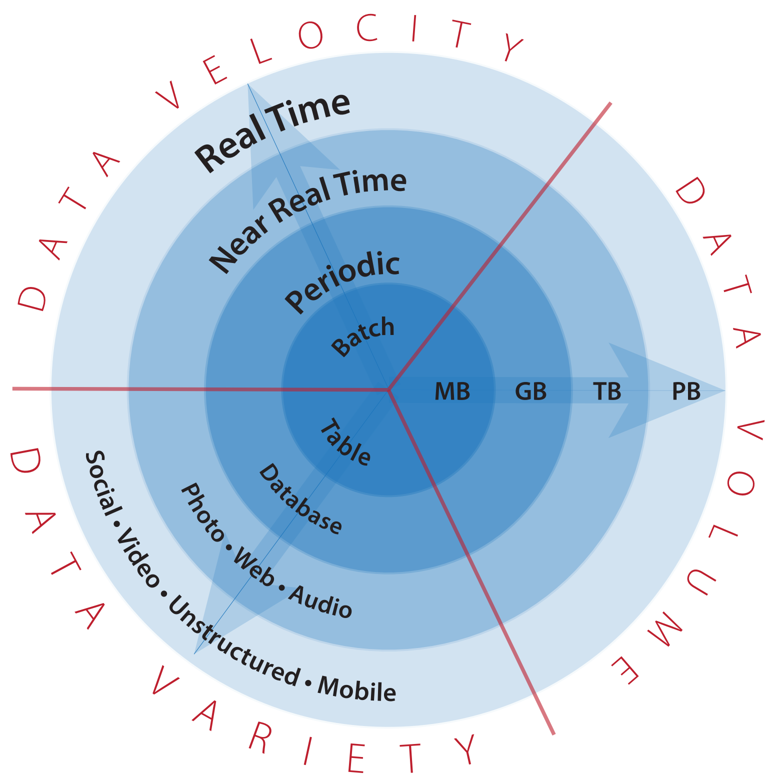
Road weather management programs also benefit from mobile sensors. Integrating mobile observations (IMO) involve collecting weather and road condition data from government fleet vehicles, such as snowplows. The focus is on supplemental data from ancillary sensors installed on the vehicles, such as pavement temperature sensors, and it also includes native vehicle data such as windshield wiper status and anti-lock brake or traction control system activation.

2.4 Categories for Emerging Technologies

Other than new data sources, many technologies are transforming ATDM practices and enhancing the state of the arts. These technologies include data technologies (e.g., big data, blockchain), decision support technologies (e.g., AI and ML), vehicle technologies (e.g., autonomous vehicles [AVs]), vehicle technologies, sensor technologies, and map technologies. Most of these technologies become relevant in the transportation field because of the increasing availability of "big" transportation data from connected travelers, vehicles, and infrastructure.

DATA TECHNOLOGIES

Data technologies (and new big data sources) are moving the transportation ecosystem at a fast rate. Emerging technologies drive virtually every other aspect of intelligent transportation. These sources range from sensing technologies such as LiDARs and lasers to mobile devices such as cell phones and iPads. These technologies are used to generate different types and volumes of data in batch, periodic, real-time, and near real-time speeds. Crowdsourcing and cloud computing are new concepts in data collection and storage, respectively. Concepts such as blockchain and big data are promising technologies that can make transportation data management and decision-making more secure and efficient than ever before. Figure 8 provides an outlook into core data characteristics in terms of velocity at which they are distributed, the variety, and the volume.



Source: Reference #65

Figure 8. Illustration. Characteristics of data.

Light Detection and Ranging

LiDAR uses ultraviolet, visible, or near-infrared light to detect objects in their sensing range. Light is reflected by the targeted object through backscattering. Using this reflected light, a point-cloud data of the object is drawn and identified by the sensor (for object recognition). Using the same approach, dynamics of moving objects are also obtained. Some uses are found in transportation planning, mapping, urban municipality, vehicle automation, and imaging. Autonomous vehicle manufacturers use LiDAR in measuring the state of moving objects around a subject vehicle.

LiDAR has been used in adaptive cruise control (ACC) systems for automobiles. One of the most important benefits of LiDAR is its safety over other surveying methods. The use of LiDAR technology for road survey has proved safe, cost-effective, efficient, and reliable. LiDAR is continually gaining widespread acceptance, especially with the emergence of CAVs and self-driving cars. LiDAR also has the potential to be used as next-generation infrastructure sensors, such as for intersection traffic monitoring. The point-cloud data generated by LiDAR can be used to track the movement of vehicles and pedestrians and, therefore, provide trajectory-level control to enable higher levels of safety and efficiency.

Laser

Known as light amplification by stimulated emission of radiation, a laser is a device that emits a beam of coherent light through an optical amplification process based on the stimulated emission of electromagnetic radiation. Applications include laser speed devices used by law enforcement to track the speed of moving vehicles. The infrared traffic logger (TIRTL) is another application that uses infrared light cones sent from a transmitter to a receiver situated on opposite sides of the road perpendicular to the flow of traffic. It classifies and records speed and volume for motor vehicles. This technology can be used to automate speed enforcement and as well as eliminate manual traffic volume data collection, which is usually time-consuming and labor intensive, and sometimes costly. Data from this source can also be used to harmonize speed in near-real time.

Automatic Vehicle Location/Global Positioning System Probe-Based Data

Automatic Vehicle Location (AVL) is a computer-based system that collects and transmits information on a vehicle's actual location. GPS on the other hand, uses signals transmitted from a network of satellites orbiting the earth. By synthesizing both technologies, providers can obtain real-time traffic data, speed and travel time roadway analytics, performance metrics, OD data, route utilization, and more. AVL systems can track the real-time position of a vehicle. It uses a wireless communication system to communicate vehicle location to a central location or control center such as TMCs. AVL is applicable in fleet management by emergency response agencies, construction agencies, and trucking companies. In some cases, AVL is used on snowplow trucks to monitor their locations. Considering its extensive use, it can serve as a rich source of probe data from all these agencies, even at weather conditions that can be harmful to other probe data sources.

Global Positioning System/Phone-Based Probe Data

Cell phone manufacturers have equipped most of their modern-day products with GPS capabilities. GPS-equipped mobile phones can provide speed and position measurements to the TMCs, allowing for better control and utilization of available infrastructure. The concept is similar to that described in the *connected traveler's* section. However, the concept here is limited to cell phones. Phone-based probe data have also been used to evaluate roadway pavement conditions by analyzing vehicle characteristics over a length of a roadway segment and recognizing inconsistencies. Identifying similar patterns in different phone-based probe data at a specific point on the roadway enables TMCs to prioritize traffic management strategy for congestion alleviation in real-time or near-real-time.

Crowdsourced Data

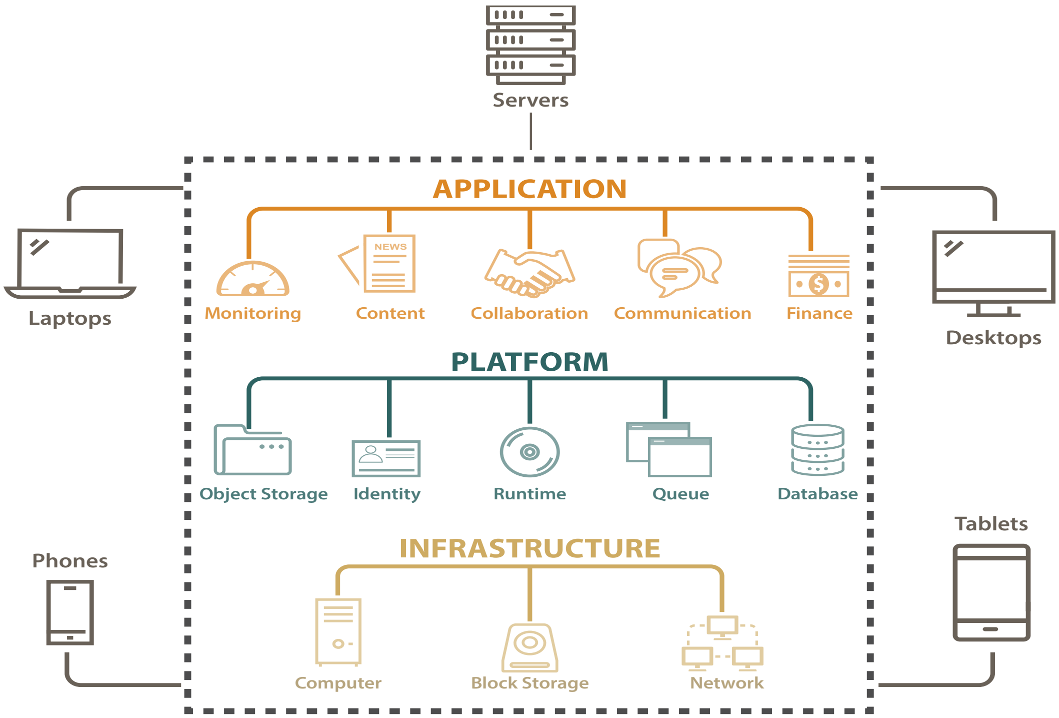
Crowdsourcing concepts coincide with cloud computing services. Crowdsourcing obtains services, ideas, and content from volunteers, part-time participants, and the general public rather than a specific group under contract, as in outsourcing, or traditional employees or suppliers. By canvassing a large crowd of people for ideas, knowledge, and skills, the quality of the information generated will be superior. Some examples of these location-aware mobile applications that provide value to the users are Moovel, Uber, or mobilty-as-a-service,[38, 39] which are originally mobility companies that provide best modes transportation options such as transit, bicycle, or taxi. Waze is another database of crowdsourced data, providing TMCs with incidents and occurrences in real time. Transportation officials can provide solutions by diverting traffic or providing alternative route advisory to road users. This is also utilized for rapid emergency response.

Internet of Things

This refers to the concept of extending connectivity beyond conventional computing platforms such as mobile devices and computers, into any range of non-internet-enabled physical devices and everyday objects. This enables an exchange of useful data between various components in a typical system without human-to-human or human-to-computer interaction. An example is the V2X communication systems. IoT enables V2X communication, which consists of V2V, V2I, and vehicle-to-pedestrian (V2P). By constantly analyzing real-time data, V2X designs a transport ecosystem where vehicles, infrastructure, and people are interconnected with each other to keep the environment safe from any type of crashes.

Cloud Computing

Cloud computing uses powerful data centers and IT infrastructure to efficiently and effectively deliver services and application to end users. It is an on-demand availability of data storage and computing power with limited active management by users. A cloud computing ecosystem (figure 9) relies on resource exchange to achieve coherence and economies of scale. This allows businesses, such as private travel information providers, to focus on developing their own application and interfaces without having to invest heavily in storage and computing facilities. The transformation of big traveler information data (which may be provided by a connected traveler) into useful resources for traffic management is made easier. Cloud computing provides agility for organizations, increased productivity, reliability, and data security, and is easy to maintain.



Source: FHWA

Figure 9. Illustration. Cloud computing ecosystem.

Big Data Technologies

This field treats ways to analyze, systematically extract information from, or otherwise deal with data sets that are too large or complex to be dealt with by traditional data-processing application software. Some of the challenges of big data include capturing, storing, analyzing, searching, sharing, transferring, visualizing, querying, updating, and sourcing the data. Big data and IoT work hand-in-hand. Data from IoT devices provide a mapping of device interconnectivity. Some of the technologies used to store and analyze data include Apache Hadoop, Microsoft HDInsight, NoSQL, Hive, Sqoop, PolyBase, EXCEL, and Presto. The big data technologies can be used to efficiently store, retrieve, and process transportation data of different formats and shared among different nodes.

Blockchain

Blockchain is a decentralized, distributed, and public digital ledger that is used in recording transactions across computers in a way that any modification cannot be done without altering subsequent blocks. It indicates a growing list of records, called blocks, which are linked using cryptography. Each block contains a cryptographic hash of the previous block, a timestamp, and transaction data. It is an open, distributed ledger that can record transactions between two parties efficiently and in a verifiable and permanent way. Blockchains are considered secure by design as they are usually developed to be resistant to modification. With blockchain, many people can write entries into a record of information, and a community of users can control how the information is modified. It can be a rich source of secure traffic data for agencies. Blockchain technologies have the potential to enhance the security and efficiency through decentralization for the next-generation traffic management systems.

Data Analytics

Data analytics is a quantitative and qualitative approach used to derive valuable insights from data and involves many processes that extract and categorize data to obtain various patterns, relations, connections, and other valuable insights. It involves using data to "tell a story" by applying algorithmic or mechanical processes to derive a conclusion. Information and conclusions drawn can be used to optimize processes to increase the overall efficiency of a business or system. Various types of analytics include descriptive, diagnostic, predictive, and prescriptive analytics. Data analytics is an extremely important domain in today's data-driven world, where 90 percent of the data has been created in the last 2 years alone. As big data begins to grow in the transportation field, the value of big data analytics will continue to develop in TMC operations and ATDM solutions.

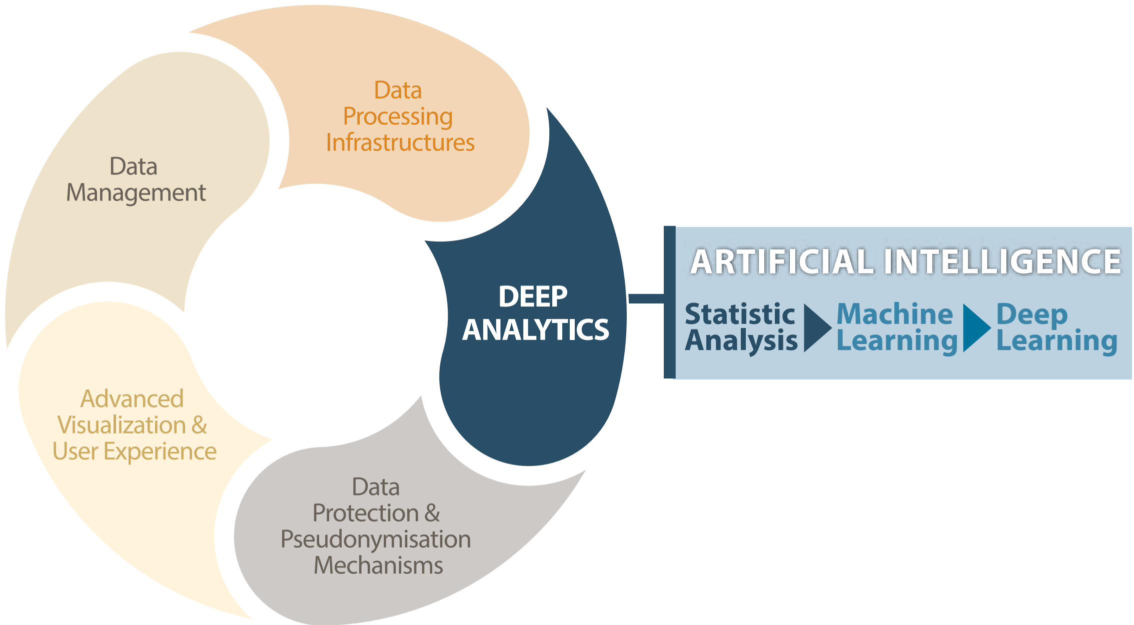
Transactional Data

Examples include commodity-specific, county-level cross-modal global freight flow data, supply chain and logistics management, purchasing behaviors, real estate marketing and valuation, and other economic transactions. Each of these may be useful to traffic management agencies and TMCs to gain a better understanding of travel patterns.

DECISION SUPPORT TECHNOLOGIES

A decision support system (DSS) or technology is an information system that supports business or organizational decision-making activities. DSS technologies serve the management, operations, and planning levels of an organization (usually mid and higher management) and help people make decisions about problems that may be rapidly changing and not easily specified in advance – i.e., unstructured and semi-structured decision problems. DSS can be either fully computerized, human-powered, or both. The advent of the web has enabled inter-organizational DSS and has given rise to numerous new applications of existing technology as well as many new decision support technologies themselves. Mobile tools, mobile e-services, and wireless internet protocols are beginning to mark the next major set of development in DSS technologies.

There are decision support technologies that help utilize the data available in a data warehouse. These technologies help executives use the warehouse quickly and effectively. They can gather data, analyze it, and make decisions based on the information present in the warehouse. AI is a major DSS technology, which has been developed over the years and improved in the past decades. Description of DSS technologies, such as ML, DL, edge computing, and voice-driven assistants, is provided in the following subsection. Figure 10 shows the place of DSS technologies in deep analytics of data.



Source: Reference #66

Figure 10. Illustration. Decision support systems position in data science.

Artificial Intelligence

AI, sometimes called machine intelligence, is intelligence demonstrated by machines, in contrast to natural intelligence demonstrated by humans. AI automates repetitive learning and discovery through data, adds intelligence, adapts through progressive learning algorithms, analyzes more and deeper data, achieves incredible accuracy, and gets the most out of data for its functionality. AI can be applied in traffic management, such as optimizing traffic SPAT, ramp metering rates, and optimal VSLs. AI systems, such as fuzzy logic and machine learning, can learn from historical data and experiences of online application, and adjust the AI model parameters to make improved decisions during the next episode (e.g., peak period traffic management). In addition to decision making, other AI technologies, such as computer vision and natural language process, to create data of increased amount and improved quality such that TMCs can implement optimal ATDM solutions on the fly.

Machine Learning

ML is technically one critical competent of AI. ML is the science of getting computers to act without being explicitly programmed. It is defined as the scientific study of algorithms and statistical models that computer systems use to effectively perform a specific task without using explicit instructions, relying on patterns and inference instead. ML algorithms use a mathematical model of sample data to make predictions or decisions without being explicitly programmed to perform the task. They are used in computer vision applications. ML models can be supervised, semi-supervised, or unsupervised, depending on the method used to train the model. ML has been used for self-driving cars, practical speech recognition, effective web search, and a vastly improved understanding of the human genome. The advent of the big data age in transportation makes ML models possible and more powerful than ever before for TMC O&M applications.

Deep Learning

DL is a specialized form of ML and is usually referred to as deep neural network. ML workflow starts with relevant features being manually extracted from some training data such as images and using them to create a model that can recognize similar images in another set of test data. This is a subset of AI and ML that uses multilayered artificial neural networks to deliver state-of-the-art accuracy in tasks such as object detection, speech recognition, and language translation. DL models are inspired by information processing and communication nature in biological nervous systems. The advantage of DL is to enhance the accuracy of the neural networks by making them deeper – forming a cascade of multiple layers of nonlinear processing units for feature extraction and transformation. DL is responsible for recent breakthroughs in AI such as self-driving cars, and intelligent voice assistants. This is mostly applicable in autonomous vehicle development, which enables learning through supervised or unsupervised approaches.

Edge Computing

This is the practice of bringing data closer to the edge of the network where the data are being generated instead of a centralized system. It is a distributed, open IT architecture that features decentralized processing power, enabling computing and IoT technologies. The benefits of edge computing are obtained from data-stream acceleration, including real-time data processing without latency. It allows applications and devices to respond to data almost instantaneously, as its being created, thereby eliminating time lag. This is a useful phenomenon for CAVs requiring real-time information use. Edge computing eliminates costs and ensures that applications can be used effectively in remote locations.

Voice-Driven Assistants

Digital experiences enabled by virtual assistants are widely considered to be among the major recent technological advances and most promising consumer trends. A voice-driven assistant is a software agent that can perform tasks or services for an individual. Also called virtual assistants or intelligent personal assistants, they can perform tasks or services for an individual based on provided verbal commands. They are able to interpret human speech and respond via synthesized voices. Users of these assistants can ask questions, control home automation devices, and media playback via voice, and manage other basic tasks. Examples include Alexa by Amazon, Cortana by Microsoft, Google Assistant by Google, and Siri by Apple Inc. Voice-driven assistants enable additional applications in TMCs. For example, users can use this capability to report road conditions such as congestion and incidents, which will then be automatically sent to TMCs for traffic management purposes. Also, voice-driven assistants can be used in vehicle information provision mode, such as reading out traffic information to the motorists to avoid driver distraction and improve message comprehensive.

VEHICLE TECHNOLOGIES

Vehicle technology has produced considerable road safety benefits. The latest trend being the V2V and V2I communication between vehicles and/or roadside devices. Also, vehicle automation technologies, such as ACC, lane-keeping, and cooperative automation applications (e.g., cooperative ACC, cooperative merge), have great potential in enhancing and transforming ATDM solutions.

These concepts make use of ideas ranging from sensing to AI to data storage. Their potential of being a source of useful data for real-time and/or near real-time traffic or transportation management and being a tool itself to regulate traffic (e.g., speed harmonization, cooperative merge) has made them a priority in the ITS and TSMO ecosystem.

Connected Vehicle Data/Technologies

- **Weather** - connected vehicle road weather applications can help reduce the impact of adverse weather on the safety and efficiency of roads. Pikalert vehicle data translator (VDT), for example, is a model that collects road and atmospheric conditions data from connected vehicles and other traditional weather information sources to infer pavement surface conditions as well as atmospheric conditions. This information is used to generate hazardous conditions alerts, and the VDT transmits them to other portions of the road weather management network. Motorists advisories and warnings (MAW) is intended to use road weather data from connected vehicles and VDT outputs to provide information to travelers on deteriorating road and weather conditions on specific roadway segments. Weather responsive traffic management (WRTM) is an application that will use road weather data from connected vehicles and VDT outputs to provide information to travelers on deteriorating road and weather conditions on specific roadway segments.
- **Safety** - Connected V2V safety applications are built around the SAE J2735 BSM. The safety applications center on BSM, a packet of data that contains information about vehicle position, heading, speed, and other information relating to a vehicle's state and predicted path. The applications have the potential to offer 360-degree awareness of hazards and situations drivers cannot see. Through in-car warnings, drivers will be alerted to imminent crash situations, such as merging trucks, cars in the driver's blind side, or when a vehicle ahead brakes suddenly. By communicating with roadside infrastructure, drivers will be alerted when they are entering a school zone, if workers are on the roadside, and if an upcoming traffic light is about to change.
- **Traffic probe** - Probe data are effective tools for urban mobility. They provide traffic information that can be used for journey planning and optimization and awareness or avoidance of incidents and delays. With the advent of connected vehicle technologies, more traffic probe data are expected to come along. Information involving both physical roadway characteristics (i.e., pavement conditions) and traffic characteristics (i.e., roadway speed), can.

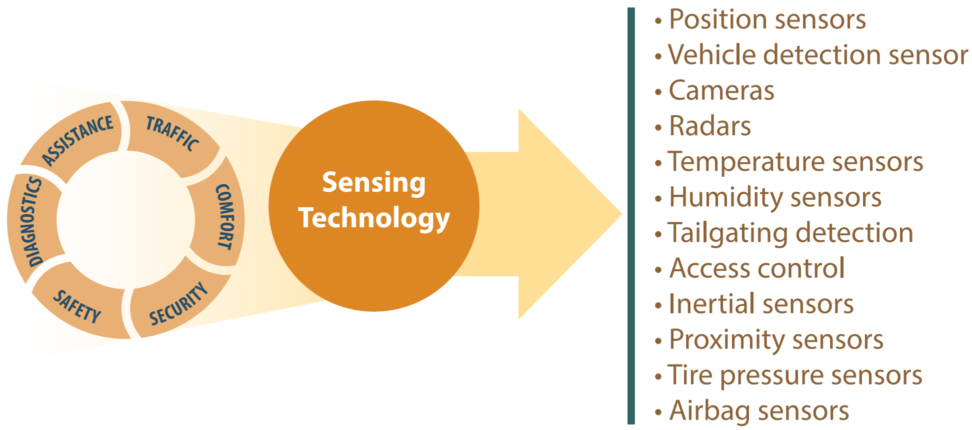
Automated Vehicle Data

Autonomous vehicles (AVs), also regarded as self-driving cars, are part of the emerging transportation technologies. AVs sense their environment using sensor technologies such as LiDAR, video image recognition (computer vision), and radar. The combined operation of this sensing capability with automated steering, braking, acceleration, navigation, and routing systems, allows a vehicle to perform the driving task with little or no human input. AV adoption offers the potential for benefits such as reduced traffic collision due to the elimination of human driver errors occurring from distraction inattention and aggressive driving, as well as better system reliability and faster perception-reaction times.[67] Further benefits expected include smarter driving and navigation, reduced needs for parking spaces, and increase transportation access to the impaired or older driver.

Data provided by navigation systems (i.e., high-accuracy GPS with inertial measurement unit [IMU]) and advanced sensors (i.e., LiDAR, and radar, camera) could be a wealth of new information that could be merged and mined for the public good, providing insights into the infrastructure, traffic flow, pedestrian movement, environment, and other elements of the developing smart cities. With real-time collection, data obtained from AVs can be sent to TMCs for active management or for a larger-scale transportation system performance evaluation.

SENSOR TECHNOLOGIES

There has been a tremendous development of sensor technologies in most of the recently launched devices. Different forms of sensing devices are being developed for different purposes. Ambient light sensors, proximity sensor, and GPS are some of the many common technologies used in smartphones. The use of sensing technologies in TSMO is witnessed in numerous aspects because they support the development and testing of emerging applications in safety, operations, and traffic control. Examples are sensors for assistance, traffic, comfort, security, safety, and diagnostics.[2] Advanced driving assistance systems are made possible by using vehicle position and detection sensors.[3] Cameras and radars are sensors used for traffic management and control. Safety applications of the sensors enable the development of automatic emergency braking systems through proximity and inertial measuring sensors.[4] Security sensors are used for access control and tailgating detection. Figure 11 shows some of the main uses of sensing technologies in transportation.



Source: FHWA

Figure 11. Illustration. Applications of sensing technologies.

Video Analytics Sensors

In many respects, the way to monitor video is similar to the way in which housing alarm technology has changed from a simple intrusion detection system in recent years into an integrated home automation solution. Likewise, video surveillance is no longer considered a way to protect the safety of people and property, but it is also a tool for improving business operations. The foundation of modern AI and ML technologies has led to a new wave of market participants and solution, part of which is in the transportation industry. Conventional traffic cameras are used to monitor visually traffic conditions in TMCs. Video analytics technologies can be applied to detect and classify individual vehicles and track vehicle trajectories at an intersection or over a stretch of highway segment, providing rich data set for next-generation TMC operations.

Air Quality Monitoring Sensors

Monitoring air quality is the systematic, long-term assessment of pollutant levels by measuring the quantity and types of certain pollutants in the surrounding, outdoor air. Air quality monitors can be used for outdoor air, indoor air, and ozone monitoring and control. Monitors are used to assess the extent of pollution, provide air pollution data to the public in a timely manner, support implementation of air quality goals, provide data to evaluate air quality models, and provide information on air quality trends. Sensor-based monitoring equipment, stations, and systems allow ambient pollution to be measured for less cost and complexity.

Smart Lighting

This is a lighting technology designed for energy efficiency. It uses high-efficiency fixtures and automated controls that adjust based on conditions such as occupancy or daylight availability. Using motion detectors, a smart lighting system senses motion and determines whether there are occupants in the space. The control unit then uses the signal to activate the switch/relay to turn the equipment on or off. This system of lighting can be very efficient in good environmental conditions. In irregular environmental conditions, there may be rapid and frequent switching, which may reduce lamp life. Smart light poles on the streets are sometimes installed with connected vehicle devices such that the control of lights can be closely tied to the ambient traffic conditions.

Bluetooth/WiFi Sensors

These sensors allow for the identification of Bluetooth or WiFi signals emanating from the traffic ecosystem. By placing sensors at different points on roadways, each signal can be identified by a sensor and reidentified by another sensor in the path, therefore, leading to the evaluation of performance such as travel time, and the understanding of route choice behavior of drivers.

MAP TECHNOLOGIES

Mapping technologies assist in representing the surface of the earth and its constituents in a format that can be more easily observed and utilized. Fundamentally, GIS is a mapping technology that digitizes and processes segmented geospatial data. It is used for location planning and in sectors such as government, transportation, natural resources, law enforcement, utilities, and communication. The first step in mapping technology is capturing data. These data types include cartographic, photographic, and digital data to provide a complete picture. Crowdsourced map data, high-resolution map data, and real-time trajectory data are some of the emerging means of acquiring map data. Accurate maps, particularly emerging HD maps, are a critical foundation for many connected and automated vehicle-related applications and ATDM solutions.

Crowdsourced Mapping Data

This provides a means to work together on the same task by the public. It allows application users to contribute information to their maps. This provides a simple way to enhance the interactivity of created maps. As citizens travel from one place to another, they can check-in on the maps and record the features observed that can serve as an update to the already existing database. Data gathered from this source can be used for TMSO. It can also become useful for autonomous vehicles navigation.

High-Definition Map Data and other Asset Management Systems

HD maps include lane-level accuracy geometry, accurate placement of all traffic control signs and advisories, allowable traffic controls at intersection junctions, and major street furniture. Such HD maps are foundational data to support automated driving and connected vehicle functions. HD maps are likely to be provided by private companies to traffic management agencies, and thus could be considered a data source. The connected vehicle “Map” message, or geometric intersection description (GID) file, is also an important element that traffic management agencies and TMCs will need to manage. HD maps are used to record the location and performance of assets at any given time. For example, sets of data such as population, the location of specific buildings, and location of utilities, can be layered on top of a standard map. HD maps can be used for facility management and planning practices, enabling organizations to be more operational savvy.

Real-time Trajectory Data

Data defined by position and momentum simultaneously. The advances in location-acquisition and mobile computing techniques have generated massive spatial trajectory data, which represent the mobility of a diversity of moving objects, such as people and vehicles. Many techniques have been proposed for processing, managing, and mining trajectory data in the past decade, fostering a broad range of applications. The data can include vehicle characteristics such as speed, elevation, and acceleration, relative to space and time.

CHAPTER 3. ACTIVE TRANSPORTATION AND DEMAND MANAGEMENT APPLICATIONS

This chapter discusses the specifics of the active transportation and demand management (ATDM) solutions and approaches and how they can be enhanced using the technologies and data sources described in chapter 2. Figure 12 depicts the challenge and tremendous opportunity that is faced by the implementers of ATDM solutions. Nearly all ATDM and/or advanced transportation management system (ATMS) deployments have the same basic functions, they:

1. Collect and monitor data from available data sources.
2. Assess system performance to identify what adverse or abnormal conditions to which and agency or system should respond.
3. Evaluate and recommend what actions to take. This is often done using response plans or Decision Support Systems (DSS).
4. Implement the dynamic actions which includes dissemination of this information via 511 systems, dynamic message signs, traveler information websites, etc.

Source: FHWA

Figure 12. Infographic. Advanced transportation demand management today and tomorrow.

Through the emergence of new data sources and technologies, the way ATDM will be performed is expected to improve. These transformational changes include:

- **Monitor System** - Today, data are pulled in from various traditional vehicle detection sensors to monitor traffic flows, speeds, and volumes. This can include inductive loops, magnetometers, radar sensors, video image detectors, etc. Also, certain probe data sources like HERE and INRIX are readily used for these same purposes. As it relates to traffic accidents and other traffic-impacting conditions like construction, computer aided dispatch (CAD) and planned lane closure (PLC) systems are used to provide this information. Also, closed circuit television (CCTV) cameras are used to gather certain information such as details related to a traffic incident.
  - ***The Future*****:** The data that informs us about congestion levels, volumes, and traffic accidents will come from the vehicles themselves (e.g., connected vehicles) and/or other applications (i.e., the smartphone navigation application Waze). Systems and sensors will be connected via IoT allowing the gathering of similar information from a variety of sources never before used as part of ATDM and traffic management systems. Lastly, crowd-sourced data will be more prominently introduced. These data sources will be more accurate and timely and will enable ubiquitous coverage of all roadways, vehicles, and facilities.
- **Assess System Performance** - Today, sensors and other technologies are used to assess system performance. Basic analytics algorithms such as ones used to calculate travel times are put in place to determine congestion levels. CCTV cameras are used to monitor roadways and potentially identify where accidents have or are occurring. In some cases, modeling tools are used to help assess system performance both in near-real-time or for after analysis.
  - ***The Future*****:** Through the use of cloud computing big data lakes,[14] on-line analytics engines, artificial intelligence (AI), and machine learning (ML), the ability to assess system performance will be easier, more intelligent, and faster and be able to take into account much larger sets of information.
- **Evaluate and Recommend Dynamic Actions** - Today, various ATDM algorithms and DSSs are used by transportation agencies to recommend dynamic actions or response plan methods. Analytic and simulation models are used to evaluate the potential effectiveness of the recommended dynamic actions. Decision support engines and algorithms determine the ATDM responses such as the activation of queue warning signs, variable speed limit (VSL) signs, dynamic lane management, parking management systems, and dynamic shoulder use.
  - ***The Future*****:** AI, ML, and deep learning (DL) may be used by transportation agencies as the basis for decision making. The key benefit here is that these systems are more intelligent; therefore, they can learn and adjust themselves over time. They can also better manage the vast amounts of information that will be available. Big Data, Cloud Computing, Data Analytics and IoT will be at the forefront of gathering, storing and better analyzing data to make decisions. Blockchain and other high-end data storage and mining mechanisms will be utilized to securely manage the volumes of information in a secure scalable manner.

- **Implement Dynamic Action** - Today, agencies implement actions such as placing messages on highway signs, enacting different traffic signal or metering plans, and notifying commuters and other agencies (e.g., police and fire) via traditional communication methods. Messages are placed on highway message signs and ATDM message signing (VSL signs, queue warning signs, lane management signs, etc.), and radio and television media and e-mail and text message systems are used, as are website and phone applications.
  - ***The Future*:** Information will be pushed automatically into vehicles, connected and autonomous. For example, the recommended speed limits messages that traditionally would be posted on overhead gantries would now be pushed into the vehicles via aftermarket devices (smartphone) or directly into the vehicle dashboard. Communication will occur with fleets of autonomous vehicles that are electric and shared (FAVES) as well as other mobility on demand services. More advanced smartphone applications will be available that enable all levels of crowd sourcing.

3.1 Active Transportation and Demand Management Approaches

This section discusses specifics on how new technologies and data sources can be used to improve ATDM solutions.

Active Traffic Management using Emerging Technologies and Data Sources

Active traffic management (ATM) deals with dynamically managing recurrent and non-recurrent congestion based on prevailing and predicted traffic conditions. It increases throughput and safety through the use of integrated systems and includes automation of dynamic deployment to optimize performance quickly without the delay that occurs when operators must deploy operational strategies manually. ATM approaches focus on influencing travel behavior with respect to lane/facility choices and operations.

The use cases and descriptions later in this section discuss operational ATM solutions and how they can be improved through the enhanced technology and data sources identified in chapter 2. It should be noted that many ATDM deployments include multiple solutions at once, i.e., a “typical” ATM corridor often employs dynamic lane use, dynamic shoulder use, VSLs and adaptive ramp metering simultaneously.

A clear example of how ATM is enhanced via an innovative new technology or data source is through the use of connected vehicle applications (e.g., vehicle to infrastructure [V2I] and vehicle to others [V2X]), which include smartphone V2X applications. Today, for most ATM applications, intrusive or non-intrusive traffic detectors are used to assess real-time traffic flows for ATM algorithms. Other incident detection methods are used to identify non-recurrent conditions such as crashes. These technologies include CAD systems, video image processing systems (VIPS), and automatic incident detection (AID) algorithms. Through the use of connected vehicle data, more granular traffic probe data can be obtained directly from vehicles. These data are much more granular and accurate; hence they can improve the timeliness and accuracy of many ATM functions. These data can augment or replace other current data sources used today. Also, dissemination of information to the motorist can be greatly improved through connected vehicle technology, including connected vehicle applications. For example, dynamic speed limits recommendation can be transmitted directly to the vehicle rather than via expensive roadside signs. Similarly, queue warning, weather warning, and dynamic shoulder use messages can go directly to the driver, which will improve overall operations and maintenance (O&M) costs. See the end of this section for descriptions of how advanced and merging technologies and data sources that can provide benefit to ATDM, mapped against the steps of the active management cycle.

Active Demand Management using Emerging Technologies and Data Sources

Active demand management (ADM) uses information and technology to dynamically manage demand, which includes redistributing travel to less congested times of day or routes or reducing overall vehicle trips by influencing a mode choice. ADM seeks to influence more fluid, daily travel choices to support more traditional, regular mode choice changes.

Some example ADM applications that can be improved via enhanced data sources and technologies include dynamic routing, pricing, and predictive travel times. Systems that have deployed predictive travel times include the San Diego Integrated Corridor Management System (ICMS), which leverages microsimulation tools and historical data to implement traffic predictions. Today, ML can be used to improve these same capabilities as can big data, cloud computing, and new probe-based data sources. Implementation of dynamic routing can be a tricky task, especially the methods that are used to recommend alternate routes. This is where the use of smartphone applications including crowdsourced applications may be beneficial. If a transportation agency desires to have traffic rerouted to avoid a serious accident, they can leverage these applications to direct drivers to the alternates that they prefer, such as alternatives where they can adjust traffic signal timings accordingly. Dynamic pricing algorithms can be improved through the use of more enriched data sources (e.g., connected vehicle data, probe data, etc.) where big data and cloud computing can be leveraged for the best dynamic pricing options/recommendations.

See the end of this section for descriptions of how advanced and merging technologies and data sources can provide benefit to ATDM, mapped against the steps of the active management cycle.

Active Parking Management using Emerging Technologies and Data Sources

Active parking management (APM) is the implementation of dynamic management of parking facilities to optimize performance and utilization of those facilities while influencing travel behavior at various stages along the trip making process: i.e., from origin to destination. Dynamically managing parking can affect travel demand by influencing trip timing choices, mode choice, and parking facility choice at the end of the trip. This ATDM approach can also have a positive impact on localized traffic flow by providing real-time parking information to users and ensuring the availability of spaces to reduce circling around parking facilities.

A key example where APM can make the best use of enhanced technologies and data sources is for dynamic wayfinding. Today, systems like the San Francisco Smart Parking and Los Angeles Express Park perform parking availability detection using traditional means such as streetline detectors or parking proximity sensors. Newer technologies can do this in a more efficient manner, e.g., CCTV cameras with video analytics can monitor large parking lot areas with a single camera.

Also, the means to direct people to available parking spaces can be done using smartphone applications in addition to roadside message signs.

Active Transportation and Demand Management Improvements using Emerging Technologies and Data Sources

See below for a depiction of advanced and merging technologies and data sources that can provide benefit to ATDM, mapped against the steps of the active management cycle.

Stage 1 - System Monitoring Enhancements for Active Transportation and Demand Management

Monitoring for system conditions such as roadway congestion levels, traffic incidents, construction activities, and weather conditions can be improved or enhanced by using these data sources or technologies:

- Light detection and ranging (LiDAR).
- Crowdsourced data, e.g., Waze.
- Automatic vehicle location (AVL) data.
- Global positioning system (GPS) probe data.
- Connected vehicle data.
- Mobile sensors/drones.
- Real-time turning movement counts.

Also, new mapping technologies such as crowdsourced mapping and high-definition (HD) mapping can assist with the common operating picture (COP) used within system monitoring tools. The use of cloud computing, big data, and data analytics can aid with performing system monitoring, especially as it relates to monitoring large amounts of complex data.

Stage 2 – Assess System Performance for Active Transportation and Demand Management

Within current ATM solutions, real-time systems utilize algorithms and other basic analytic tools to assess system performance. This can include real-time COP mapping for observing conditions as they unfold. There are some modern and emerging technologies that can improve how, and how accurately, performance is assessed. Some of the best emerging technologies include the use of big data and data analytics engines to assess the vast amounts of data that are being collected. In the future, there will likely be much larger and more granular data available from likely sources such as connected vehicle data. One of the key benefits of big data analytics is that they can aid at providing insights into data correlations that humans would not naturally see.

Other key technologies that can aid in assessing system performance are AI tools, which include ML and DL. Through programming with AI tools, the conclusions of system performance can be greatly improved. One example is that AI can aid with prediction of traffic conditions and events, which is a much more proactive approach, i.e., ATDM systems will then be able to assess not only current performance but future performance.

Performance can also be assessed in real-time using more advanced video analytics technology, which includes solutions that can identify traffic flow performance issues or other traffic event or incident issues. This includes wrong way driving, stalled vehicles, fire and smoke detection, etc.

Stage 3 – Evaluate and Recommend Dynamic Actions for Active Transportation and Demand Management

The next stage of the active management cycle is to evaluate and recommend dynamic actions based upon the performance assessments completed during Stage 2. This is where DSS can be improved. AL, ML, and DL can enhance DSS, which includes the concept of basing decisions on future predictions rather than just upon current conditions only. On-line microsimulation tools offer a way to assess and evaluate strategies in real-time to determine which strategies will work most successfully.

Cloud computing and more advanced data analytics can be used as well to evaluate the dynamic actions. With the appropriate computing power and/or cloud computing environments, these analytics can be done very quickly. Edge computing can also be used to analyze conditions and behavior such as video analytics, pedestrian detection, and poor local traffic signal performance.

Stage 4 – Implement Dynamic Actions for Active Transportation and Demand Management

New emerging technology can be used to implement the ATDM actions as well. This includes the following:

- Recommendations on how drivers should behave can be pushed into vehicles using connected vehicle applications or directly into vehicle dashboards that will be equipped in the future to receive and display these messages. These messages can include VSLs, queue warning, motorist warnings, weather warnings, and signal phasing and timing (SPaT).
- Edge computing is now being used to implement actions at the edge. For example, DMSs related to ATDM functions can be activated directly using edge computing rather than via centralized systems. Traffic signal adjustments and preemption can also be done at the edge. Moving computing and decision making to the edge can be more efficient, decrease costs, and speed system response.
- Narrow AI in the form of voice driven assistants can help with quickly implementing dynamic actions. Activation can occur with a single voice command that can replace 10+ mouse clicks on the system user interface.
- Smartphone applications and connected citizen applications can be used to implement alternate applications. For example, advanced parking applications can be used to notify motorists of available parking as well as arrange reservations and payment in advance. The same applications can be used to recommend mode shift and alternate routing.
- Feedback into crowdsourcing applications may also be useful. For example, informing the navigation crowdsourcing applications like Waze as related to blocked lanes or road performance deficiencies can assist with more effective ATDM implementations.

USE CASES

This section discusses use cases for applying emerging technologies and data sources to improve how ATDM is accomplished. The use cases provide examples of what is being used now, and what can be enhanced using new technologies and data sources.

USE CASE 1: RECURRING CONGESTION ON FREEWAYS AND HIGHWAYS

Brief Description

On weekday mornings, recurring freeway congestion occurs as commuters travel into the metropolitan area to report to work.

Actors

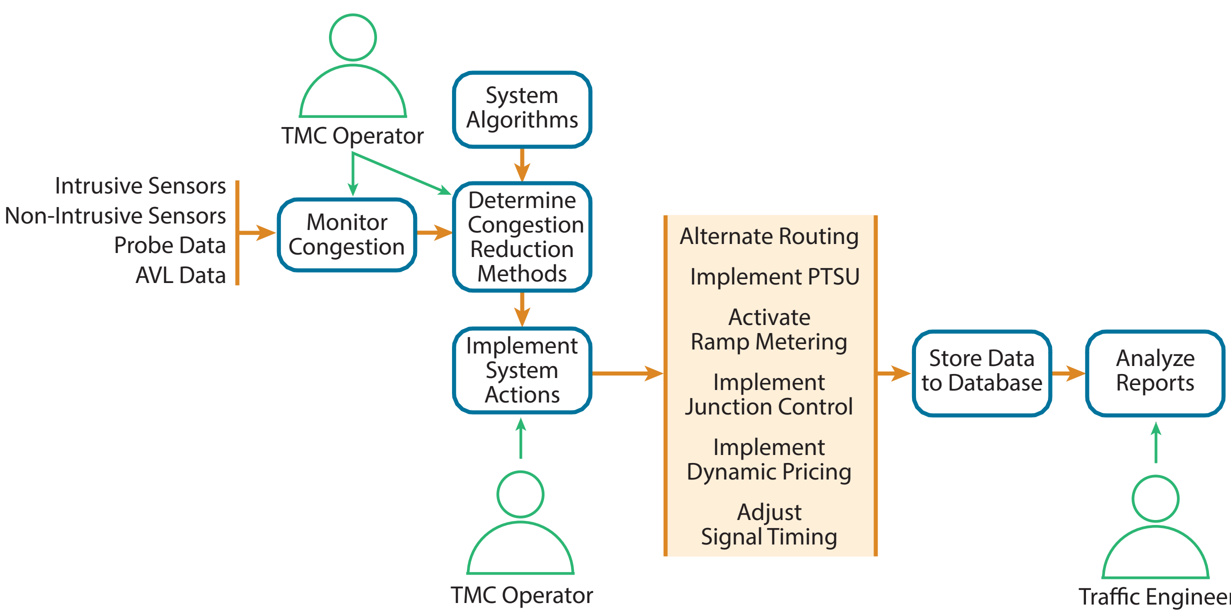
1. Motorist.
2. Transportation management center (TMC) operator.
3. Traffic engineer.

Pre-conditions

1. ATMS software is running in the TMC, and a TMC operator is able to take actions to reduce the congestion.

Basic Flow: Currently in Use

Figure 13 is a representation on this use case without advanced or emerging technologies and data sources applied.



Source: FHWA

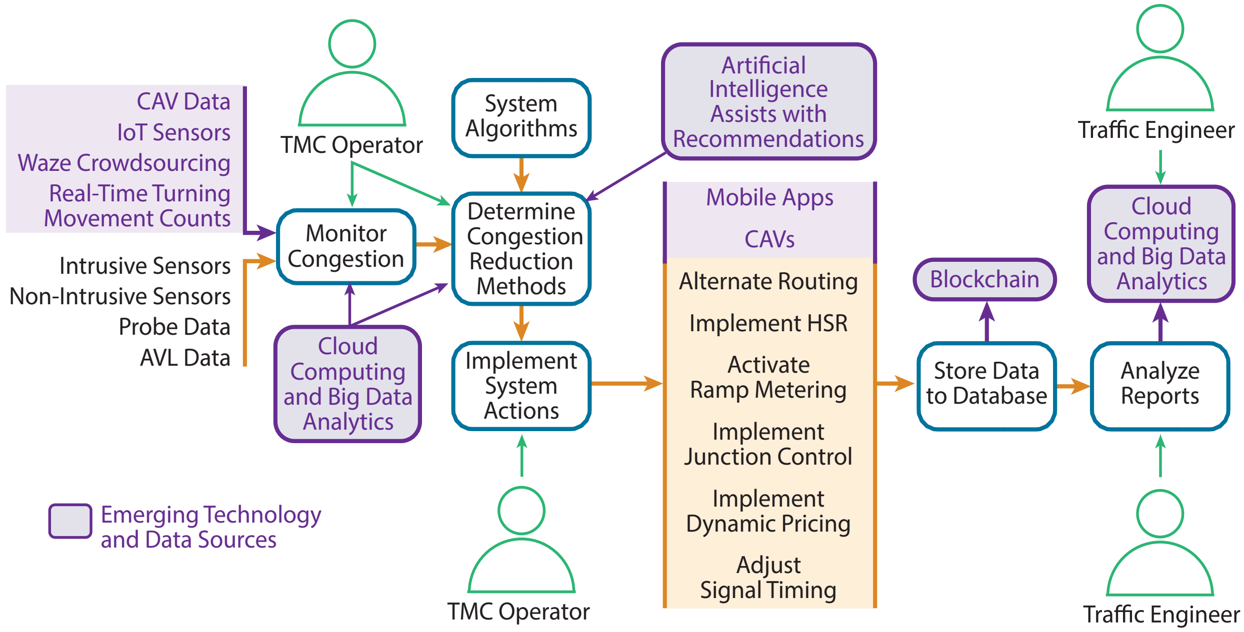
Figure 13. Diagram. Recurring congestion use case (traditional).

A description of the stages follows:

1. Traditionally, vehicle detection devices such as inductive loop sensors, radar sensors, or video analytic sensors detect congestion buildup on the freeway and alert the TMC operator of the congestion build up on an ATMS map. Cameras along the roadway can also be used to confirm the congestion.
2. The TMC operator enters or confirms a congestion event (the existence of excessive congestion) into the ATMS and generates the recommended actions to implement.
3. System actions are recommended to help deter or reduce the congestion levels or minimize its impact.
4. Several potential strategies are implemented to address congestion:
    a. Activate or adjust ramp metering rates.
    b. Implement junction control.
    c. Implement dynamic pricing.
    d. Implement part time shoulder use.
    e. Implement dynamic speed limits.
    f. Implement alternate routing.
5. The TMC operator monitors the impact of the strategies that are deployed.
6. Data are stored in a historical database. Traditional reports can be used to determine performance metrics.

Basic Flow: Emerging Technologies and Data Sources

Figure 14 is a representation on this use case with advanced or emerging technologies and data sources applied.



Source: FHWA

Figure 14. Diagram. Recurring congestion use case with new data and technology.

A description of the stages follows:

1. Traditionally, vehicle detection devices such as inductive loop sensors, radar sensors, or video analytic sensors detect congestion buildup on the freeway and alert the TMC operator of the congestion build up on an ATMS map. Cameras along the roadway can also be used to confirm the congestion.
2. New data sources are also used to assess congestion levels, including:
    a. Crowdsourced data (e.g., Waze).
    b. Connected and autonomous vehicle data.
    c. Real-time turning movement count data.
    d. Data analytics from cloud computing.
3. The TMC operator enters or confirms a congestion event (the existence of excessive congestion) into the ATMS and generates a traditional logic-based response plan.
4. The response plan is recommended to help deter or reduce the congestion levels or minimize its impact. Traditional DSS methods are used, as are AI, ML and DL methods. Data Analytics and on-line microsimulation helps to help assess and evaluate the recommended action plan.
5. Several potential strategies are implemented to address congestion:
    a. Activate or adjust ramp metering rates.
    b. Implement junction control.
    c. Implement congestion pricing.
    d. Implement dynamic shoulder use.
    e. Implement dynamic speed limits.
    f. Implement dynamic routing.
    g. Send recommendations using smartphone applications.
    h. Send connected vehicle messages to smartphones and aftermarket devices.
6. The TMC operator monitors the impact of the strategies that are deployed.
7. Data are stored in a historical database. Traditional reports and cloud-based data analytics methods are used to determine performance metrics.
8. Blockchain data storage can also be used, especially as it relates to more sensitive data and data that warrant more secure storage.

Post Conditions

Successful Condition

Congestion is detected more quickly.

Congestion and delay levels are more accurate.

More appropriate implementation actions are recommended and implemented.

The system learns and improves itself over time.

Better analytics and reporting.

Recurring freeway congestion is measurably reduced.

Failure Condition

Detection times and congestion level accuracy are only marginally improved.

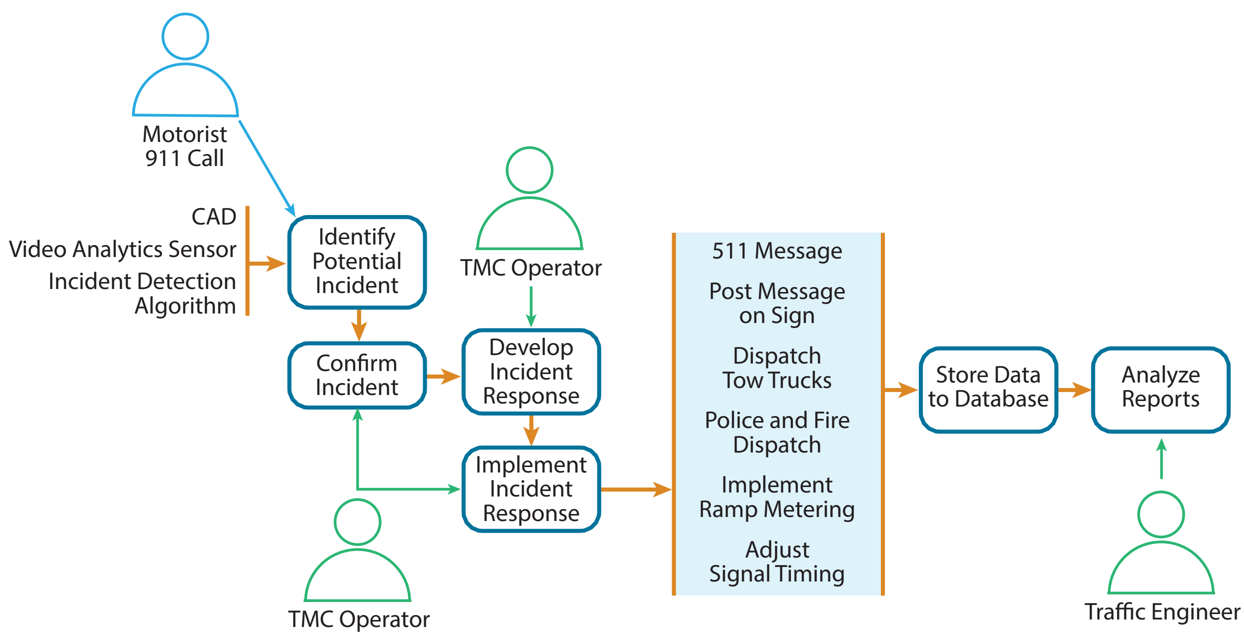
Freeway congestion is not reduced.

Implementation improvements are only marginal when compared to cost.

USE CASE 2: MAJOR INCIDENT ON FREEWAY

Brief Description

A typical ATDM use case is related to how a major freeway incident is detected, the decisions made on how to respond to the incident, and the method(s) to respond to the incident. Figure 15 represents a use case on how a typical freeway incident is handled, keeping in mind that there are different options and variations that can be employed.



Source: FHWA

Figure 15. Diagram. Incident management use case (traditional).

Actors

1. Motorist.
2. TMC operator.
3. Traffic engineer.

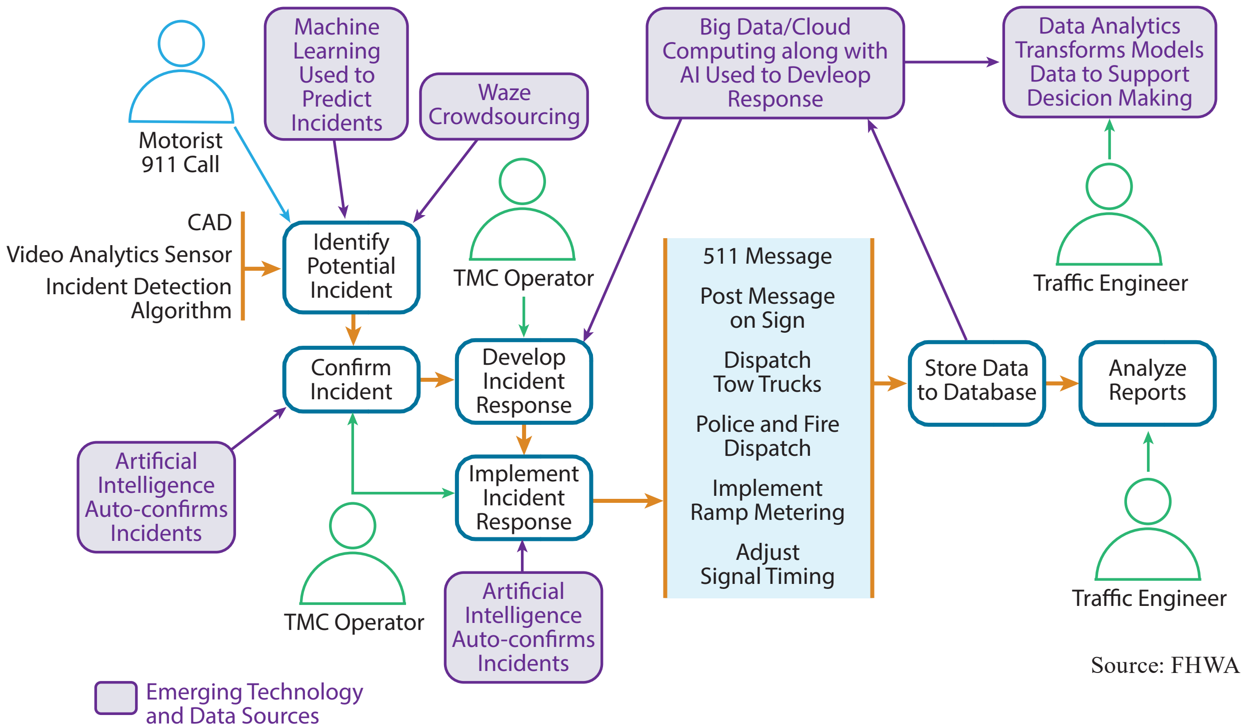
Preconditions

1. ATMS software is running in the TMC, and a TMC operator can take actions that are used manage the incident. The following actions are available for incident response:
    a. Post a 511 message.
    b. Post a message on a sign.
    c. Dispatch tow trucks/service patrol vehicles.
    d. Dispatch fire and/or police.
    e. Implement ramp metering.
    f. Adjust signal timing.

Basic Flow: Currently in Use

1. Traditionally, a potential incident is identified by the following mechanisms:
    a. A traveling motorist calls 911 to report the incident.
    b. Data are received from law enforcement agencies' computer aided dispatch (CAD) system.
    c. Video analytic sensors detect congestion buildup.
    d. Vehicle detection devices such as inductive loop sensors and radar sensors detect congestion buildup on the freeway and alert the TMC operator of a potential incident using an incident detection algorithm.
2. The TMC operator confirms the incident.
3. The TMC operator generates a traditional rules-based response plan.
4. The response plan is implemented by the TMC operator:
    a. Post a 511 message.
    b. Post a message on a sign.
    c. Dispatch tow trucks.
    d. Dispatch fire/police.
    e. Implement ramp metering.
    f. Adjust signal timing.
5. Details regarding the event and its response plan are archived into the database.
6. Traffic engineers can generate traditional reports that can be used to determine performance metrics.

Figure 16 characterizes the same freeway incident management use case but introduces new data sources and technologies.



Source: FHWA

Figure 16. Diagram. Incident management use case (new technology and data sources).

Basic Flow with Emerging Technologies and Data Sources

1. A potential incident is identified by the following mechanisms:
   - A traveling motorist calls 911 to report the incident.
   - Data are received from law enforcement agencies' CAD system.
   - Video analytic sensors detect congestion buildup.
   - Vehicle detection devices such as inductive loop sensors and radar sensors detect congestion buildup on the freeway and alert the TMC operator of a potential incident using an incident detection algorithm.
   - ML is used to predict incidents.
   - Waze crowdsourcing is used to identify incidents.
2. The TMC operator confirms the incident:
   - AI auto-confirms the incident.
3. The TMC operator generates a traditional rules-based response plan:
   - Big data in the cloud computing environment, along with artificial intelligence are used to develop a response based on historical and predictive data.

4. The response plan is implemented by the TMC operator:
    - AI auto-implements the incident response:
        i. Post a 511 message.
        ii. Post a message on a sign.
        iii. Dispatch tow trucks.
        iv. Dispatch fire/police.
        v. Implement ramp metering.
        vi. Adjust signal timing.
5. Details regarding the event and its response plan are archived into the database:
    - Data are archived into the Cloud where they are available for input into predicting incidents or generating response plans.
6. Traffic engineers can generate traditional reports that can be used to determine performance metrics:
    - Data analytics transform and model data to support decision making.

Post Conditions

Successful Condition

The incident is cleared, and traffic is cleared in a timely manner.

Failure Condition

The incident is cleared, but not in a timely manner, or causes additional incidents.

USE CASE 3: PARKING NEAR THE AIRPORT

Brief Description

In preparation for a week-long trip, a traveler is examining options for parking his vehicle near the airport.

Actors

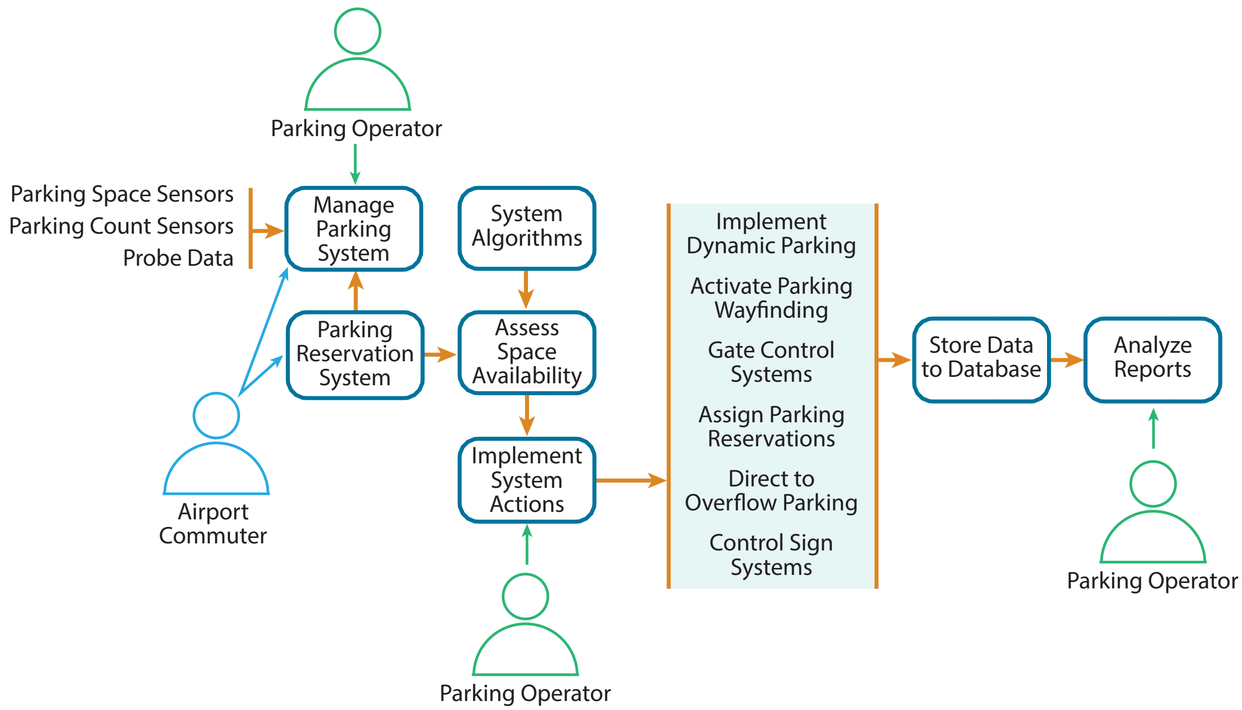
1. Traveler.
2. Parking system operator.

Preconditions

1. Parking facilities exist near the airport.

Basic Flow: Currently in Use

Figure 17 depicts a typical airport parking use case.



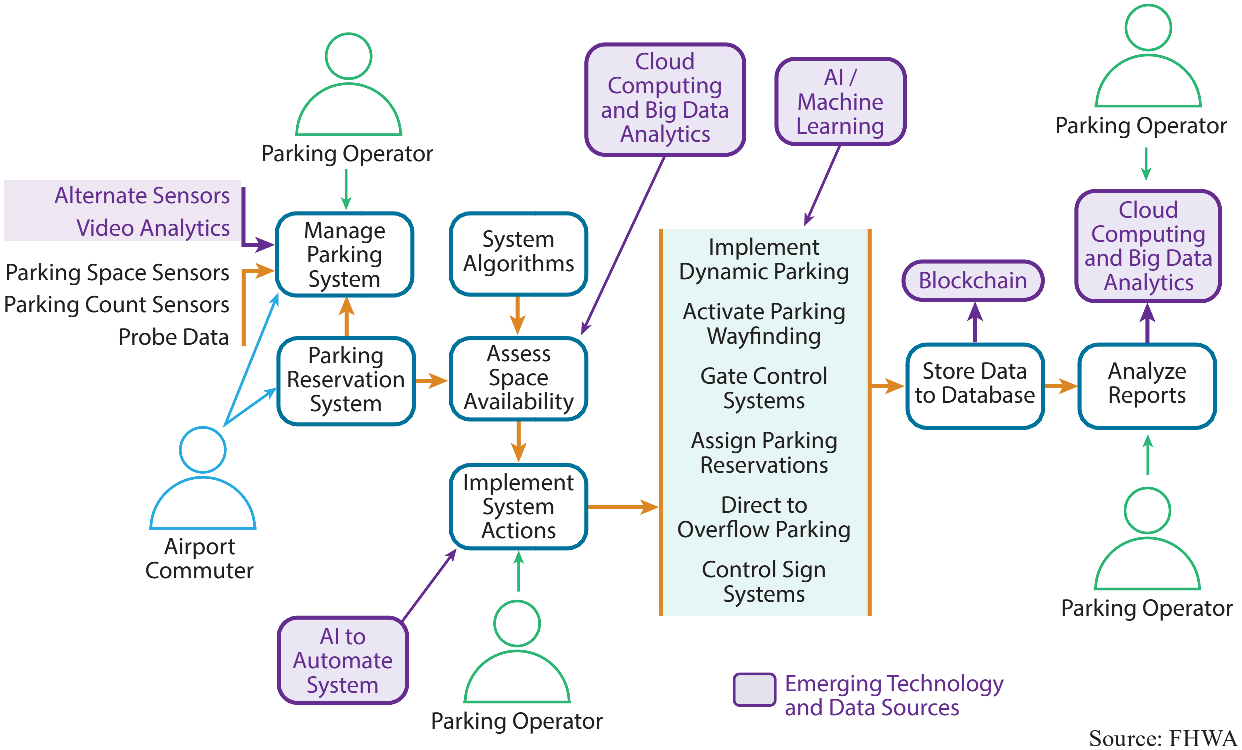
Source: FHWA

Figure 17. Diagram. Airport parking use case (traditional methods).

1. Sensor systems are constantly monitoring the spot usage and availability using traditional sensors.
2. In advance, the traveler manually selects a parking provider that provides the ability to reserve a parking spot in advance. This reservation may or may not be at the closest facility to the airport. The fees are generally based on a fixed schedule; however, some facilities have currently implemented dynamic pricing.
3. Alternately, the driver proceeds to the airport and pays fees directly at parking structure.
4. Based upon parking availability and pre-existing reservations, the system provides direction to the driver, e.g., proceed to this level, aisle, and spot.
5. If parking is full, driver is directed to another off-site parking option.
6. Depending on demand, dynamic priced parking may be activated.
7. The traveler then parks his vehicle in the reserved spot.
8. Data are stored for further analysis by the parking system operator.

Basic Flow: Emerging Technologies and Data Sources

Figure 18 represents the same parking system use case but uses merging technologies and data sources.



Source: FHWA

Figure 18. Diagram. Airport parking use case (new technologies and data sources).

1. Sensor systems are constantly monitoring the spot usage and availability using traditional sensors.
2. New technologies and data sensor types are used to monitor system parking availability, including video analytics sensors and LiDAR.
3. In advance, the traveler manually selects a parking provider that provides the ability to reserve a parking spot in advance. This reservation may or may not be at the closest facility to the airport. The fees are generally based on a fixed schedule; however, some facilities have currently implemented dynamic pricing.
4. Alternately, the driver proceeds to the airport and pays fees directly at parking structure.
5. Based upon parking availability and pre-existing reservations, the system provides direction to the driver, e.g., proceed to this level, aisle, and spot.
6. AI is used to automate all parking system actions.
7. Cloud computing and data analytics are used to predict parking availability and adjust dynamic priced parking to maximize revenue.
8. If parking is full, driver is directed to another off-site parking option.
9. Depending on demand, dynamic priced parking may be activated.

10. The traveler then parks his vehicle in the reserved spot.
11. Data are stored for further analysis by the parking system operator.
12. Secure data such as transactions and license plate reads are stored using block chain.
13. Data are analyzed using data analytics and cloud computing.

Post Conditions

Successful Condition

The vehicle is able to park in the reserved spot.

Failure Condition

The reserved spot was not available, leaving the driver to search for another.

CHAPTER 4. PLANNING AND ORGANIZATIONAL CONSIDERATIONS

Planning for an active transportation and demand management (ATDM) implementation is a complex process and involves advanced planning. Because ATDM expects new solutions involving emerging data sources and technologies, it may bring with it new planning steps and modified organizational approaches to deploying agencies. This chapter includes the following sections:

- **Organizational Capability** - Provides an overview of the organizational capability concepts that support successful ATDM operations.
- **Planning for Modified ATDM Operations** - Discusses specific efforts that an agency undertakes to plan for operations, including scenario planning and use of data.
- **Setting Objectives and Performance Measures** - Describes the importance of identifying objectives and performance measures for operations.
- **Analysis, Modeling, and Simulation** - Discusses the types of analyses that an agency can conduct to assess the feasibility and potential impacts of ATDM solutions on specific corridors.
- **Programming and Budgeting** - Describes strategies for programming and budgeting for ATDM solutions on a regional basis.

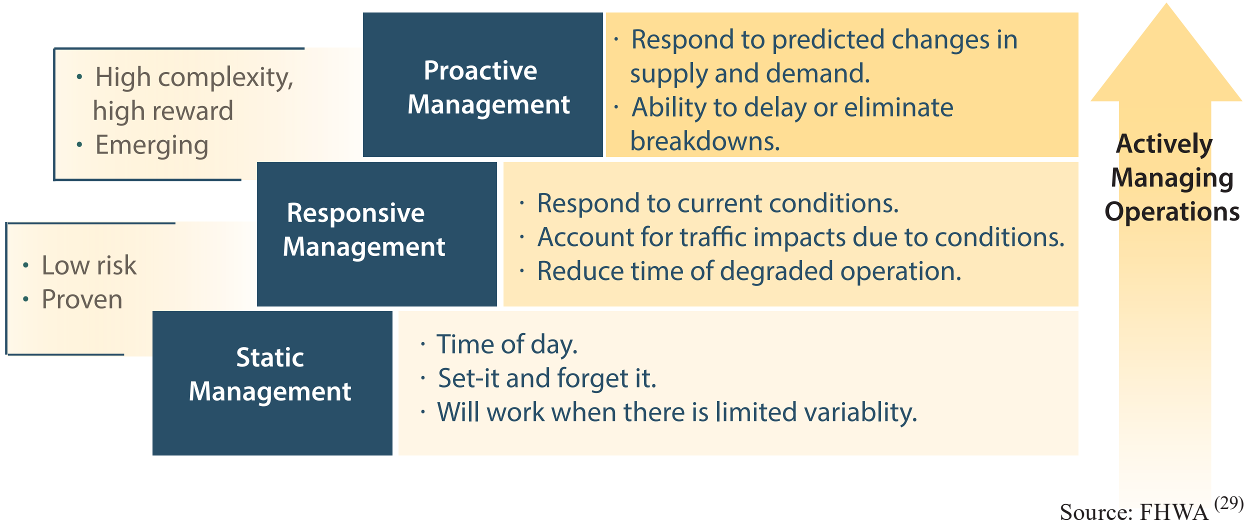
An excellent reference across all the above-mentioned topics is FHWA's Organizing and Planning for Operations website.[1]

4.1 Organizational Capability

ATDM is a more integrated approach toward real-time operations and rests on a foundation of robust systems management and requires a degree of organizational maturity to be successful. To adjust to ATDM solutions, organizations are required to proactively manage transportation systems.

Figure 19 illustrates a stair-stepped approach towards increased active management: static management, responsive management, followed by proactive management. Agencies with a very low level of capability in systems management and operations are probably not ready for ATDM deployment, lacking the adequate business processes, supporting technology, and required workforce to be effective.

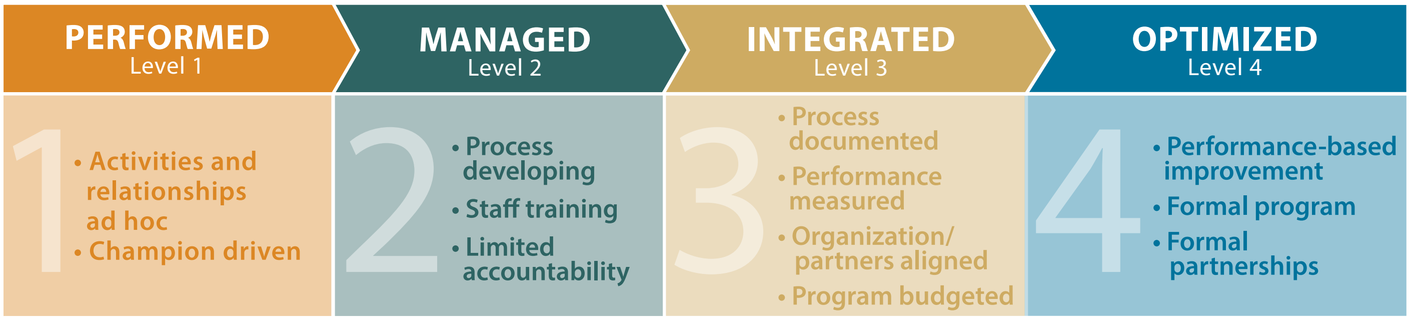
1 U.S. Department of Transportation Federal Highway Administration Organizing and Planning for Operations. https://ops.fhwa.dot.gov/plan4ops/active_trans.htm.



Source: FHWA [29]

Figure 19. Diagram. Steps for actively managing operations.

FHWA has developed a Traffic Management Organizational Capability Maturity Model (TM CMM) to aid in assessing an organization and a set of tools that can assist transportation agency managers with self-assessments of their organization's development.[61] Four dimensions that are most relevant to ATDM implementation are: (a) staffing, (b) education, (c) organizational changes, and (d) new business processes. These tools can be used by agencies to address the non-technological challenges involved in ATDM. The levels of organizational maturity defined by the FHWA TM CMM, as shown in figure 20, move from level 1 with some programs mostly information and champion driven, to level 2 with some developed processes, to level 3 where performance is measured and programs are formally budgeted, to level 4 where formal partnerships exist and performance-based improvements are the norm.



Source: FHWA

Figure 20. Diagram. Levels of organization maturity.

The FHWA Traffic Management Capability Maturity Framework (TM CMF) is structured around these four levels of organizational maturity. Based on the level at which an agency resides for each dimension, a list of actions that the agency can undertake to advance its capabilities to the next level is provided.

The four factors of organizational capability (staffing, education, organizational changes, and new business processes) can be used to help agencies identify the current state of their operations programs and provide guidance for improved levels of program effectiveness.

STAFFING

Improvements to transportation management functions and traffic management center (TMC) operations are not only brought about through new physical components, hardware, and software but also through people—their training, skills, and core competencies. The following staffing questions serve to prepare the staff for ATDM:

- How prepared are agency TMC users for emerging data (e.g., their challenges, technical skills, etc.)?
- What is the expected user experience for agency operators? User experiences are as important as data and systems integration in the success of new software functions.
- What are the desired outcomes of the end user's tasks (e.g., will they impact other aspects of the organization or other users)? Designing the user interfaces and business process flows to be intuitive is an important element in software adoption.
- How will agency users access the big data systems and tools (e.g., local client software, intranet, internet)?

EDUCATION

The challenges of maintaining a skilled workforce equally apply to ATDM operations, which will likely require a greater number of skilled staff, specifically at the TMC. Dynamic operations, which are likely to be 24 hours a day, 7 days a week, can require more staffing and skills an agency may not have. Also, the technologies supporting these solutions may be more complex than traditional intelligent transportation system (ITS) deployments. Comprehensive training is needed for agency staff to become familiar with the functionalities of new systems before deploying new ATDM solutions. The following questions focusing on education aid an agency planning for ATDM:

- What skills in databases, software installation, software maintenance, application scripting, dashboarding, and analytics does the agency already have? How can personnel with such skills be obtained?
- Is there flexibility to acquire agency staff with these skill sets (i.e., redefine roles, expand technical staff groups)?
- Is there a mechanism to obtain these skills if they cannot be addressed by current staff or roles (i.e., contract/outsource, training)?

ORGANIZATIONAL CHANGES

Agency culture is important in promoting ATDM throughout an organization. A new role as an active operator of a system or network to improve throughput, reduce congestion, and increase travel time reliability requires leadership vision, communications, and changes in the organizational structure. ATDM deployments benefit from support from the respective agency decision makers, and constant engagement and communication are essential to promote ATDM as a core operating philosophy. Increased education and outreach to policy makers and decision makers within the agency can help to facilitate this cultural transition.

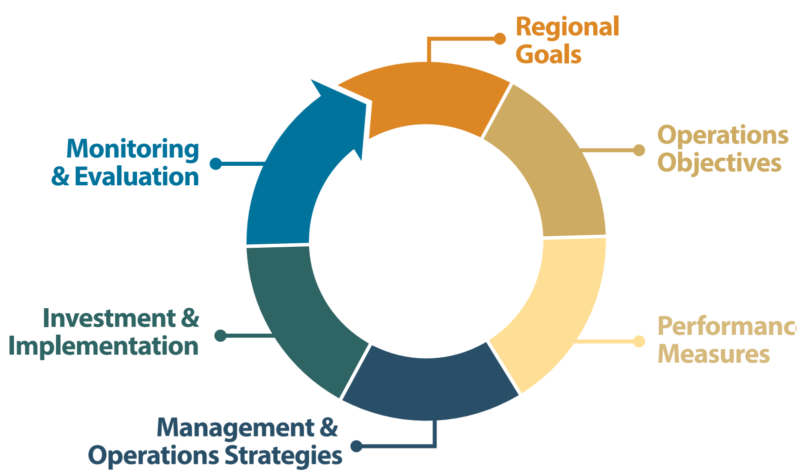
NEW BUSINESS PROCESSES

Scoping, planning, evaluating, and budgeting processes are key business process elements to examine. Given the broad range of operational strategies and the experimental nature of ATDM solutions, agencies may need to address and modify business process elements for greater consideration and adoption of ATDM solutions.

Business processes that drive the scoping, planning, evaluating, and budgeting processes are key elements to examine. Evidenced from the various statewide operations plans and ITS strategic plans, the role of operations strategies is increasingly becoming clear. With the emphasis on planning for operations, leading State Departments of Transportation (DOTs) are developing robust practices to include operations strategies in planning, programming, and prioritizing. As defined in the FHWA TM CMF, the optimized organization has formalized processes, programs, partnerships, and a demonstrated record of performance-based improvements, ready for ATDM.[68]

4.2 Planning for Modified Active Transportation and Demand Management Operations

Planning for ATDM operations benefits from leveraging of ongoing efforts and institutional partnerships in a region. These partnerships serve as the foundation for such efforts as freeway management and operations, regional traffic incident management, and arterial traffic management and operations. Planning for operations is structured around an objective-driven, performance-based approach, as illustrated in figure 21. The rationale for this approach is to link planning and operations to improve transportation decisions to effectively enhance the overall network by ensuring investments work to meet regional goals and objectives.



Source: FHWA

Figure 21. Diagram. Object-driven, performance-based approach to planning for operations.

As a result, a program plan that incorporates ATDM solutions will typically go beyond traditional infrastructure and deployment needs and identify how agencies and regions can address ATDM project planning, lifecycle costing of equipment and other infrastructure investments, and operations and maintenance (O&M) of the ATDM solutions. Specific aspects of planning for ATDM operations can include scenario planning, new data uses, new technology uses/expertise, training, and information technology (IT) considerations.

SCENARIO PLANNING

Scenario planning can be helpful in the development of ATDM solutions. Scenarios can vary by specific environmental or background characteristics, such as deploying ATDM solutions during planned events (work zones or special demand generator) and in response to incident or emergency conditions (closed lanes or inclement weather). Preferably, agencies should describe ATDM operational scenarios from a user perspective, inclusive of typical day-to-day operations. A predetermined ATDM operational plan can detail how normal, or recurrent, ATDM operations would function in addition to specific scenarios that would necessitate change or unique application. For example, if dynamic shoulder use is to be deployed along a facility, the operating agency should determine how that shoulder will be managed in the event of an incident.[36] Potential scenarios could include (a) opening the shoulder to traffic if not already operational to help alleviate congestion caused by the incident, or (b) closing the shoulder to traffic if already open to accommodate emergency response personnel to access the incident. In either scenario or some other variation, the operating agency needs to determine how the strategy will be deployed, for what purpose, and for what duration, and identify other stakeholders and that partners need to be incorporated into the decision to implement the scenario. Planning elements that may be included within an ATDM scenario plan are agency roles and responsibilities, traveler information needs specific to the dynamic nature of the ATDM solutions, system interoperability (how different components of the ATDM solutions interact and communicate with other ITS infrastructure in place and any legacy systems), stakeholder roles, and risk allocation. Simulation exercises can help agencies assess various ATDM scenarios and operational strategies by evaluating the impact of specific components or the inclusion of select user groups.

NEW DATA USES

The use of data for planning ATDM solutions principally involves collecting accurate and reliable data. Overall, data needs are linked to monitoring and modeling needs. Data enhance an agency's ability to determine the extent and duration of congestion and system performance and to estimate potential performance benefits on the network of an ATDM strategy. For operational purposes, data often require detailed granularity that can allow analysts to examine the potential for incremental changes at specific locations. Longitudinal data are necessary for seasonal and year-to-year comparisons. Data needs are typically driven by the establishment of performance metrics, as defined by the regional needs and goals of the project or program.

Sources for data can vary. Data for ATDM may originate from regular data collection programs or special studies, usually in conjunction with implementing a new ATDM strategy. A range of entities can provide data on a continual or regular basis and may include internal agency groups or private third parties. Examples include travel demand models, TMC data, transit ridership records, crash records, third-party mobility data, or citation data. More agencies are relying on private entities to provide data, particularly for measuring mobility and congestion. Agency coordination is important in the planning phase to facilitate data sharing, help determine ATDM solutions to implement and prioritize corridors and areas for those solutions. As ATDM solutions are incorporated into the planning process, agencies should ensure that data are identified and collected to support the performance measures used in that process.

NEW TECHNOLOGY USES AND EXPERTISE

New technology uses and expertise consider how agencies are responding to the upgrading, replacement, and integration of systems in the world of rapidly changing technologies.

Nationally, operations agency personnel and management have a basic, but growing, understanding of the systems approach, architecture use, and standardization, especially for ITS projects that are Federally funded and, thereby, require the use of systems engineering. While some operational strategies have become fairly standard and commonplace, the ongoing maintenance, management, replacement, and upgrading of systems is a challenge to most organizations, and these challenges will most likely also apply to ATDM solutions, which involve new technology that is unfamiliar to many agencies. Additionally, the dynamic nature of ATDM solutions involves significant sensor and communications investment that increases the complexity of the ITS infrastructure needed to operate the systems. Thus, agencies may want to ensure that the capabilities are in place to support these complex systems and ensure reliable operations to optimize performance.

TRAINING

Different areas of staff education and training should also be considered, which impacts costs. Active traffic management (ATM) solutions generally involve more complex ITSs that may be unfamiliar to agency planners, designers, construction personnel, and TMC operators. The following are specific training efforts that an agency might consider:

- Peer-to-peer exchanges with other transportation agencies that operate similar ATM deployments, to include document sharing, teleconferences, webinars, or site visits for key agency personnel.
- Structured mentoring and training between experienced operators and junior operators to formally provide junior operators additional learned knowledge regarding complex operations, automated features, and decision support system (DSS) responses.
- Cross-training to ensure sufficient operations staff are available to facilitate 24 hours a day/7 days a week operations and to cover in the event of staff absences or departures.
- Safety training for personnel in the field, including maintenance staff, law enforcement, incident response teams, emergency management, and transit drivers, especially if ATM in any way impacts how they conduct their job duties.

4.3 Setting Objectives and Performance Measures

Performance measures and system performance monitoring are crucial components of planning for operations.[28] Performance measures are indicators of how well the transportation system is performing and are used in several ways in the objectives-driven, performance-based approach to planning for operations:

- Track progress toward operations objectives.
- Identify needs and system performance deficiencies.

- Assess potential impacts of O&M strategies.
- Evaluate effects of implemented projects.
- Communicate progress to stakeholders.

Performance measures are inextricably tied to operations objectives. ATM solutions usually need more regular monitoring and maintenance of performance, given the significance of overall program goals and scrutiny of newly implemented solutions.

The importance of the quantitative nature of performance measures cannot be understated, as is clearly explained in chapter 4 of FHWA's *Freeway Management and Operations Handbook*.[22]

SETTING OBJECTIVES AND PERFORMANCE MEASURES FOR ACTIVE TRANSPORTATION AND DEMAND MANAGEMENT

Performance measures for ATDM solutions should be SMART (specific, measurable, attainable, realistic, and time-bound), should clearly relate to agency goals and objectives, and shall be driven by the capability to collect the data and conduct analyses. Key groups of measures include travel time reliability, congestion management, safety, and sustainability and livability.

In particular, the *Active Traffic Management (ATM) Implementation and Operations Guide. Report FHWA-HOP-17-056* identifies multiple performance measures used in Europe for ATM deployments: [17, 37]

- Speed differential between lanes.
- Duration of speed less than x mph.
- Frequency of speed less than x mph.
- Flow/speed plots.
- Lane utilization.
- Headway distribution.
- Vehicle speed distribution.
- Vehicle hour delay.

The *Highway Capacity Manual* contains a chapter on ATDM that recommends four measures of effectiveness for evaluating ATDM-related objectives: [9]

- Person miles traveled (PMT).
- Average delay per mile traveled.
- Average system speed.
- Planning time index (PTI).

In addition to these measures, the *Guide for Highway Capacity and Operations Analysis of Active Transportation and Demand Management Strategies* recommends: [23]

- Vehicle-miles traveled (VMT)-demand.
- VMT-Served.
- Vehicle-hours traveled.
- Vehicle-hours delay.
- Vehicle-hours of entry delay.
- Vehicle-hours delay/vehicle-trip.
- 80th percentile travel time index.

RECURRING CONGESTION – OBJECTIVES & PERFORMANCE MEASURES

Travel time reliability – A key aspect of performance that symbolizes the larger effect of day-to-day variation in travel conditions. Traditional measures related to travel speed and delay do not capture the dimension of reliability, therefore, other metrics are typically used. Specific characteristics help guide the selection of travel time reliability performance measures, as defined by specific goals, availability and quality of data, and geographic scope and intent of the program. The buffer index (BI) is a measure of travel reliability that can account for the varied distribution of travel times. The PTI represents how much total time a traveler should allow for ensuring on-time arrival, as opposed to more time represented from the BI. PTI is useful because it can be compared to the travel time index. Example objectives and performance measures related to travel time reliability include:

Objective	Performance Measure
Improve efficiency for passengers and freight	• BI • PTI • Travel time index

Congestion Management – Beyond travel reliability, multiple dimensions of mobility should be assessed within an ATDM performance measurement program. Commonly, an appropriate characterization of performance should include the extent of congestion, or the size of the population and user groups impacted by degraded conditions. Example objectives and performance measures related to congestion management include:

Objective	Performance Measure	
Reduce congestion	• Highway delay • Travel speed • Vehicle-hours of travel • Passenger travel times	• Person throughput • Number of bottlenecks • Customer satisfaction

NON-RECURRING CONGESTION – OBJECTIVES AND PERFORMANCE MEASURES

Non-recurring sources of congestion, such as work zones, special events, and adverse weather, share a common set of objectives and with them corresponding performance measures. Many non-recurring events can be expected and, with preparation, bring specialized opportunities to measure and respond. Example objectives and performance measures related to non-recurring congestion include: [32]

Objective	Performance Measure
Reduce roadway clearance time:	Time between first recordable awareness of incident by a responsible agency and first confirmation that all lanes are available for traffic flow.
Reduce incident clearance time:	Time between first recordable awareness of incident by a responsible agency and time at which the last responder has left the scene.
Reduce number of secondary crashes:	Number of unplanned crashes beginning with the time of detection of the primary incident where a collision occurs either (a) within the incident scene or (b) within the queue, including the opposite direction, resulting from the original incident.

SAFETY – OBJECTIVES AND PERFORMANCE MEASURES

Safety is an important goal that often justifies the purpose and funding of implementing an ATDM strategy. Compared to mobility and congestion, assessing safety-related performance usually requires years to collect enough baseline data to justify a statistical sound evaluation process that supports valid conclusions. The selection of specific metrics is related to the overall safety goals for the program, the availability and quality of data, and the type of geography for the assessed ATDM strategy. Example objectives and performance measures related to safety include:

Objective	Performance Measure
Reduce fatalities and injuries on all public roads	• Incident rate • Incident detection/response/clearance • Total fatalities and serious injuries • Excess travel time due to incidents • Percent vehicles exceeding speed limit by x%

LIVABILITY – OBJECTIVES AND PERFORMANCE MEASURES

Performance related to livability may be tied to metrics that assess environmental characteristics. Oftentimes within an ATDM context, environmental measures include elements that entail emission of volatile compounds and local impacts on noise. An assessment of air quality entails quantifying the change in ozone precursors over time, specifically nitrogen oxides and carbon monoxide. Energy and fuel use, as measured by gallons of gasoline, is another metric that can be associated with assessing environmental impact. Example objectives and performance measures related to livability include:

Objective	Performance Measure
Environmental sustainability Enhance performance while protecting and enhancing the natural environment	• Level of emissions • Number of days exceeding air quality

4.4 Analysis, Modeling and Simulation

FHWA and its State and local agency partners have relied on analysis, modeling, and simulation (AMS) to support investment decisions for the transportation system. As the transportation system environment grows in complexity, increasing pressure is placed on agencies to identify more innovative and efficient solutions to a wide range of issues. These solutions include leveraging emerging technologies, data sources, and alternative (non-traditional) strategies. AMS tools will continue to play a critical role in evaluating these solutions. In fact, section 1430 of the Fixing America's Surface Transportation (FAST) Act (Public Law 114-94) includes the sense of Congress that the Department of Transportation utilize AMS tools "to the fullest and most economically feasible extent practicable" to analyze highway and public transportation projects[2].[(46)] As transportation solutions become more sophisticated and complex, corresponding AMS tools will need to evolve; AMS tools must be able to effectively and fully quantify the benefits of proposed solutions.

Traffic analysts depend on software and analytical tools and methodologies to investigate the performance of present transportation facilities and predict the possible improvement from future implementations. The objectives for using these tools is to facilitate the decision-making process, evaluate and prioritize planning and operational alternatives, improve evaluation time, reduce cost, reduce traffic disruption, present transportation strategies to road users or stakeholders, and monitor roadway performance.

Dozens of AMS tools and methodologies designed for conducting analysis of one or more ATDM solutions have been identified to date. These tools and methods can generally be segmented into three broad categories:

- **Sketch-planning methods –** These analysis methods provide simple, quick, and low-cost estimation of ATDM strategy benefits and costs. Often based in a spreadsheet format, these methods typically rely on generally available input data and static default relationships between the solutions and their impact on a limited number of measures of effectiveness (MOEs) to

2 https://highways.dot.gov/operations/analysis-modeling-and-simulation/analysis-modeling-and-simulation-overview

estimate the benefits of the solution. A number of established benefit/cost (B/C) tools, including Tool for Operations Benefit Cost Analysis, Screening Tool for ITS, and California Lifecycle Benefit Cost Analysis, are classified as sketch-planning methods; however, this category also includes scores of individually developed and customized spreadsheet and simple database methods configured to support various analyses by single agencies. The Highway Capacity Manual (TRB. 2016) provides methodologies and software components for analyzing ATDM solutions, therefore it falls under this category.

- **Post-processing methods –** These methods are often more robust than sketch-planning methods, as they seek to more directly link the B/C analysis with the travel demand, network data, and performance measure outputs from regional travel demand or simulation models. Several established tools, including ITS Deployment Analysis System and the FITSEval application, have been designed to directly accept detailed model data as inputs to the analysis. The tools then provide additional analysis within their framework to assess impacts to MOEs outside the capabilities of typical travel demand models. Outside of these more established tools, these post-processing methods also include customized applications, algorithms, and routines that may be applied directly within a region's existing modeling framework to produce the required MOEs. These methods are often more capable of assessing the impacts of route, mode, or temporal shifts than sketch-planning methods.
- **Multiresolution/multiscenario methods –** These analysis methods are often the most complex of the methods and are typically applied when a high level of confidence in the accuracy of the results is required. These methods are most often applied during the final rounds of alternatives analysis or during the design phases when detailed information is required to prioritize and optimize the proposed solutions. Multiresolution methods depend on the integration of various analysis tools (e.g., linking a travel demand model and a simulation model, including mesoscopic or microscopic simulation tools) to provide meaningful analysis of the full range of impacts of an operational strategy – capturing both the long-term impacts on travel demand, along with the more immediate impacts on traffic performance. Meanwhile, multiscenario methods seek to assess strategy performance during varying underlying traffic conditions. In this analysis, the impact of a particular ATDM strategy may be tested under a variety of conditions (e.g., incident versus no-incident, good weather versus rain conditions versus snow conditions) to fully capture the benefits under all the likely operating conditions. This type of analysis often requires that the analysis model be run multiple times to capture these effects.[10]

Table 5 shows the appropriate geographic scope and resources required for each of the three types of AMS tools. These two factors are critical in selecting appropriate methods/tools for use.

Table 5. Analysis, Modeling, and Simulation Tools and application attributes.

AMS Tool	Geographic Scope	Resources Required
Sketch-Planning Methods	• Isolated location • Corridor • Subarea • Regionwide	• Budget – Low ($1K to $25K) • Schedule – 1 week to 8 weeks • Staff expertise – Medium • Data availability – Low

Table 5. Analysis, Modeling, and Simulation Tools and application attributes (Continued).

AMS Tool	Geographic Scope	Resources Required
Post-Processing Methods	• Corridor • Subarea • Regionwide	• Budget – Medium/High ($5,000 to $50,000) • Schedule – 2 months to 1 year • Staff Expertise – Medium/High • Data Availability – Medium
Multiresolution/ Multiscenario Methods	• Corridor • Subarea	• Budget – High ($50,000 to $1.5 million) • Schedule – 3 months to 1.5 years • Staff Expertise – High • Data Availability – High

A recent FHWA effort was dedicated to developing AMS testbeds for the dynamic mobility applications (DMA) and ATDM programs[3]. The primary objective of this project is to develop multiple simulation testbeds/transportation models to evaluate the impacts of DMA connected vehicle applications and ATDM solutions. The objective of this study was to analyze the approaches and requirements for forecasting transportation conditions and predicting system performance to support real-time performance-based management. The concept is for the TMCs to have a comprehensive view of the transportation system in real-time and use that view to predict how the system will behave (i.e., the performance of the transportation system) within the next 20 minutes, 30 minutes, or 1 hour. If the predicted performance over that time does not meet the desired performance target, the TMC operator/manager can proactively implement operational solutions or actions to influence and alter the future performance in a favorable manner to align with the performance objectives/goals. These actions may include providing real-time information about the predicted conditions to travelers, implementing operational strategies such as congestion pricing, parking information/restrictions, hard shoulder use, speed harmonization, ramp metering and control, optimizing traffic signal timing, changing transit frequency, adjusting the mix of transit services, etc.

Through this project, six virtual testbeds were developed and used for DMA and ATDM evaluation. The testbeds are diverse in terms of their geographic scope, modeling tools, modeled applications, and solutions, and answered research questions and produced over 24 deliverables to the U.S. Department of Transportation. FHWA also published a Primer to help public agencies understand how the portfolio of products developed under this project can be useful in conducting their own ATDM analysis.

Additionally, the Traffic Analysis Tools Program was formulated by FHWA in an attempt to strike a balance between efforts to develop new, improved tools in support of traffic operations analysis and efforts to facilitate the deployment and use of existing tools. The FHWA Traffic Analysis Toolbox has many useful guidance documents. Through the FHWA Traffic Analysis Tools Program, agency partners and customers will expand their use of analysis tools and innovative analysis approaches

3 https://ops.fhwa.dot.gov/atdm/research/index.htm

that consider a system-level approach and will enhance mobility. They will gain insight on recommended/best practices and lessons learned in operational analysis. They will gain a high level of confidence in utilizing the analysis tools for their local needs. The proactive role from FHWA will enable analytical tools and DSSs to reach their full potential to support a viable transportation community in a manner sufficient to make a significant contribution to evolving traffic congestion and management problems.

4.5 Programming and Budgeting

Partnerships and collaborations are often essential to implementing ATDM, particularly through the programming and budgeting process. Securing funding for transportation projects is highly competitive given the nature of limited and constrained resources. Federal policy mandates and guides many components of planning, programming, and funding projects. ATDM solutions can be included within an improvement or long-range plan once an agency or project sponsor determines that it can complement or improve upon Statewide, regional, or local goals. However, ATDM solutions will have to compete with other projects to gain approval for funding.

The processes that make up the programming elements of planning will differ from State to State and will entail the steps that agencies must undergo to select projects for funding. Project sponsors often develop a decision-based framework with financial considerations for implementation. States and regions, as represented by metropolitan planning organizations (MPOs), coordinate their efforts through the development of the long-range transportation plan, taking into consideration changes in overall demand and improvements to the transportation system. MPOs are required to develop short-range transportation improvement programs (TIPs) that can include select ATDM solutions if those projects are estimated to have a high priority[4].[(40)] States are also required to develop similar short-range plans, commonly known as a Statewide transportation improvement program (STIP)[5].[(42)]

In developing full lifecycle budgets for ATDM, agencies considerations cannot be limited to acquisition costs. Instead, the programming and budgeting process must consider the costs:

- New recurring costs.
- New operations and maintenance (O&M) cost and models.
- New capital costs.
- System refresh costs.

4 23 USC 134(j)

5 23 U.S.C. 135(a)(1)

CHAPTER 5. DESIGN AND DEPLOYMENT ELEMENTS AND METHODS

Within this chapter, the design and deployment elements and the methods to facilitate and optimize the use of emerging data sources and technologies are detailed. Design elements can be described as the logical and/or physical (e.g., agencies) data elements. The deployment elements are described as the data sources themselves, the system platforms, and infrastructure. This section discusses these challenges in detail and informs agencies of potential solutions and common approaches to modern active transportation and demand management (ATDM) technology and data enhancements.

Before delving into the details of elements and methods, the findings documented in FHWA's case study "*Demonstrating Performance-Based Practical Design through Analysis of Active Traffic Management," FHWA-HOP-1-087* are important to introduce.[15] This case study illustrated how a performance-based practical design approach was used to analyze and make tradeoffs when examining potential active traffic management (ATM) strategies. By considering decision criteria in design rather than after deployment, the implementing agency able to optimally provide the greatest benefit.

5.1 Design Elements

Earlier chapters in this document have identified and described in detail the emerging technologies and data sources. Many of these technologies are transforming ATDM practices and enhancing the state of the art. These transformations are forcing agencies look to consider ATDM deployments in new ways. Two high-level technology challenges that should be initially considered include:

1. **Logical Data Management (LDM)** - How the agency scopes and prepares data in a manner that supports analysis as a system including geographic, temporal, jurisdictional, functional and modal boundaries.
2. **PDM** - How the agency designs technology systems that support scalable, cost-effective, and high-performance ingestion, transformation, analysis, storage, and sharing of data with increasing value across the five V's (discussed below).

LOGICAL DATA MANAGEMENT

Agencies should fully investigate the implications of LDM as the initial step of any ATDM objective. In 2017, FHWA published *Scoping and Conducting Data Driven 21st Century Transportation System Analysis,*[31] which describes a continuous improvement process (CIP) to integrate data-driven time-dynamic operational analyses within transportation systems management.

To illustrate the importance of LDM for data scoping, consider a task to integrate connected vehicle data for ATDM. Based on the desired outputs from analyzing connected vehicle' data, the process and technologies implemented to manage the data may differ greatly. High-resolution connected vehicle' data in raw format, for example, may provide real-time congestion reporting at 100 samples per second, or accelerometer and gyroscope data, which could be leveraged to automatically detect accidents and abnormal driving. For a region, this could result in the need to manage massive data set. Without scoping data management, an agency may not fully understand if storage and processing raw data is necessary, or if aggregating and processing data at the edge would provide the necessary data resolution. Considering the magnitude and velocity of data from sources described in section 2.3 of this document, the scoping of data management will have significant operational and cost implications.

Analysis of data for ATDM will largely involve spatiotemporal data sets. For example, modern approaches to incident management may involve correlation of location-based sensor data, including vehicle detection through probe or sensor data, connected vehicle data, crowdsourced data, and other correlation data such as regional events, emergency room capacity, etc. The analysis of spatiotemporal data requires that both temporal and spatial correlations be considered. Analysis based on temporal and spatial dimensions of data adds significant complexity to the data analysis process. Scoping the approach used to enhance, store, and share regional spatiotemporal data is critical to successful implementation of modern ATDM projects.

The FHWA guidance, *Scoping and Conducting Data-Driven 21st Century Transportation System Analyses,*(31) provides information about using the outcomes of the CIP process to drive the selection and implementation of the physical data management tasks described below.

PHYSICAL DATA MANAGEMENT

The emergence of the transportation data sources identified earlier indicates that Departments of Transportation (DOTs) will soon be facing significant big data challenges of their own, specifically as it relates to ATDM. Connected travelers, vehicles, and infrastructure will drive growth in data that will enhance transportation systems management and operations (TSMO), but these new data require an information technology (IT) infrastructure, processes, and skills capable of handling data acquisition, marshaling, and analysis. The remainder of this section discusses the physical data management model for modern transportation data, industry and government developments in big data, and emerging data analysis techniques.

Characteristics of Big Data

As stated in *Integrating Emerging Data Sources into Operational Practice – State of the Practice Review, FHWA-JPO-16-424,*(24) the first four V's (volume, velocity, variety, and veracity) are attributes of the data itself, each requiring additional considerations to supplement and modernize traditional systems. While the fifth V (value) is the business benefit that can be created using big data.

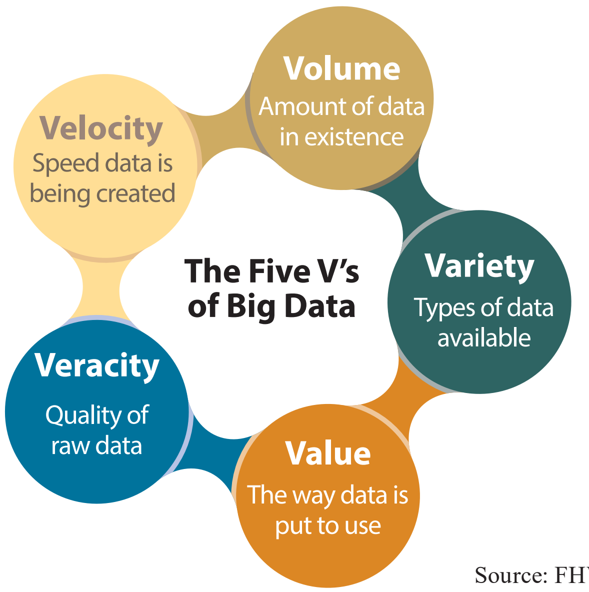


Figure 22. Illustration. The five "V's" of big data.

Descriptions of the five V's follow:

- **Volume** - The total amount of data in existence. Data are constantly being generated at faster speeds, and organizations are interested in collecting more of it for analysis. Infrastructure scalability becomes paramount as data volumes increase exponentially and storage priorities must be adapted.
- **Velocity** - The rate at which data are generated and the rate at which the data need to be processed. There are primarily two categories of data processing, batch and streaming. Batch processing is for analysis done after-the-fact and in large chunks at a time. Data that do not require immediate action can be analyzed independently from the real-time performance of the system. Streaming processing enables real-time decision making and alerts by analyzing the data as soon as they arrive. Streaming and batch analyses each have their pros and cons, and the appropriate method depends largely on the organization's particular use case and business need. Transportation management centers have needs for both streaming and batch data processing and use cases for both will be explored further in a subsequent report.
- **Variety** - The different data sources (e.g., connected vehicles, connected travelers, and connected infrastructure) and types of data being generated. When an organization is interested in collecting as much data as possible for analysis, the ability to store and analyze a wide variety is an important factor to consider. Other considerations include storage capabilities for structured, unstructured, and semi-structured data and advanced analysis techniques to make use of complex data (e.g., unstructured image files).
- **Veracity** - The quality of the raw data being received. This includes challenges organizations face collecting information they can trust with data free of biases, noise (background data that are impossible for machines to understand), abnormalities, or general inaccuracies. Veracity also can refer to the collection of unwanted data. Organizations may want to collect as much data as possible but may not know what to do with it all once they have it. This is particularly

true in our use cases for TSMO specifically related to the collection of basic safety messages (BSM). This will be explored further in subsequent reports. Veracity can play a particularly important role in automated decision making without human interaction and intervention (e.g., adaptive traffic control, automated incident alerts, or future concepts for regional congestion pricing or road user charging).

- **Value** - The potential that big data offer to unlock new insights, make faster and smarter decisions, and improve practice in TSMO. Volume, velocity, variety, and veracity make big data into the beast that it is to manage. However, to create value out of the emerging data sources, TSMO organizations may wish to manage the four V's in a way that maximizes the return on investment of data as an asset.

5.2 Data Sources

Organizations planning for ATDM will face a number of hurdles when turning their big data opportunities into meaningful actions. Without proper planning and consideration, a big data solution can turn into an inefficient system with latency and performance issues. Just like a transportation solution for congestion in a growing city, a big data solution should be thoughtfully designed before any physical construction takes place. The process model depicted in table 8 is a useful way of thinking through a big data solution by breaking it into four distinct steps.

Table 6. A big data process model: acquisition, marshaling, analysis, and action.

Acquisition	Marshaling	Analysis	Action
Collecting data from sources.	Sorting and storing of data.	Finding insights/ predictive modeling.	Using insights to change business outcomes.
• Traditional extract, transform, and load, but often real-time 'constant acquisition' due to volume and velocity. • As data are often external, there are issues of security and trust. • Licenses for data use; privacy issues for data exist.	• Large volumes/ constant feed. • Data filtering may reflect how data will be consumed (real-time, as soon as possible, historical). • Formal structured, semi-structured, and unstructured data. • Modeling (from raw form to highly structured depending on source and use). • Data lifecycle (transient versus long-term storage/ archival).	• Perform analytics for hindsights, insights, and foresights. • Text, voice, and video analysis capabilities. • Predictive modeling - more probabilistic than definitive.	• Use insights to make real-time decisions (e.g., automatic routing of vehicles based on road conditions and accidents). • Generate real-time alerts and notifications (e.g., work zone alerts and traffic delays).
Master Data Management and Data Governance			

ACQUISITION

Acquisition refers to the collection and preprocessing of data from a variety of systems within the organization (internal sources) and systems outside the organization (external sources). External sources of data frequently require more consideration due to differing data formats, more privacy, governance, and security concerns (e.g., rights to use and distribute, sensitivity of the data, corrupt or malicious files, etc.). Additionally, methods for ingesting data are continuing to evolve and depend on many factors: (1) the volume of data coming in; (2) the data source; (3) how quickly data are needed; and (4) how much preprocessing of data is necessary (e.g., extract/transform/load [ETL]) before being ready for analysis. The methods and characteristics of how data are acquired are important to consider because they can directly affect the capabilities and considerations for how data is marshaled, analyzed, and acted upon. Currently, data acquisition (or 'constant acquisition') for TSMO agencies is in the form of polling field devices using National Transportation Communications for intelligent transportation system (ITS) protocol or proprietary protocols, accessing data feeds from third parties using Web services, and sharing traveler conditions data with other systems.

These questions are intended to be representative, thought-provoking, and extensive, but not exhaustive. More will likely be developed and adapted based on the results of emerging technologies and data sources within ATDM.

- **Acquisition**
  - Where do your data currently come from?
  - Are you interested in acquiring any new data sources?
  - How much data will you be ingesting?
  - What format(s) are these data in?
  - What tools will you use to ingest the data?

MARSHALING

Marshaling refers to the sorting and storing of data. The five V's are of particular importance when it comes to marshaling the data. The high volume, fast velocity, diverse variety, and questionable veracity of big data require a robust and adaptable storage solution to harness its value. A big data solution should be capable of storing all types of data an organization is interested in collecting at the speed needed to collect and process it for actionable insights. This includes the ability to compress and archive legacy data as well as newly collected data that are not necessary for immediate or frequent analysis.

- **Marshaling**
  - Where do you plan on hosting your data, locally or in the cloud?
  - Will the data need to be preprocessed in a specific way (e.g., ETL), normalization, merging, imputation, etc.)?
  - How often do you anticipate needing to scale your solution up or down?
  - What level of latency are you comfortable with in accessing the data?
  - Will your data sources provide you with structured, unstructured, and/or semi-structured data?
  - How long will the data reside in your solution?
  - What are your organization's security and data governance standards for the data collected; for example, where do the data need to go when you are finished with it?
  - What is your archival procedure and governance strategy?
  - What is the acceptable loss in functionality/availability of your system?
  - What is the criticality of data loss; for example, will your solution be a system of record for any data?

ANALYSIS

Analysis refers to how an organization wants to use their data, including the ability to find insights and inform decisions through advanced analytical techniques and visualization. Analysis can be performed at many different speeds and can use a wide variety of tools and techniques. One set of methods uses statistical, descriptive, and predictive models to provide hindsight, insight, and foresight, respectively. For example, predictive models may one day be used to forecast traffic conditions based on weather, incidents, historical traffic data, and other factors. Additionally, new techniques are rapidly emerging to analyze data previously considered too difficult, including unstructured data like text, audio, and video. Improvements in video analytics technologies may make streaming video from closed-circuit television (CCTV) more valuable than it is today. With properly designed acquisition, marshaling, and analysis methods, tools such as live, interactive dashboards can be designed to minimize the time from data ingestion to actionable insights. This is similar to what Performance Measurement System and Transportation Information System are doing for TSMO agencies today with traditional databases and acquisition methods.

- **Analysis**
  - What are the current languages, analyses, and tools/technologies you are currently using?
  - How complex are your current analyses and how frequently do you currently process data?
  - What analytical and programming languages are you interested in using (e.g., Java, SAS, R, Python, Scala, etc.)?
  - What analytical skills are you interested in expanding or willing to expand to?
  - How advanced will your data analysis procedures be (e.g., machine learning (ML), natural language processing, etc.)?
  - Do you intend to perform media (e.g., audio, video, imagery, etc.) analysis, text analysis, or a combination of both?
  - Do you want to maintain manual or automated control over your analytical algorithms and procedures?
  - How quickly do you need to perform certain analyses (e.g., real-time, 24-hour cycles, etc.)?
  - What is the criticality for interruption of analyses; for example, how mission-critical are the analyses you are performing?

DATA STORAGE

Given that the data being collected by the regional systems are coming in various formats (e.g., tabular, video, text, etc.) and types (e.g., structured and unstructured), the process of cleaning, organizing, storing, and managing these data will be of major consequence to the operational success of the regional systems and, by extension, the State DOT repository. Conventional wisdom for all data stored and processed in this scenario is that the data should be secured, fault-tolerant, scalable, and backed up. Additionally, there may be a benefit at the regional traffic management center (TMC) level of compressing and archiving data locally while the responsibility of long-term data storage lies at the Statewide level.

Regional systems need to support terabytes (TBs) of data arriving daily. Assuming an initial data size of 100 TBs (data that already exist within these regional systems) and a daily intake of 2.2 TBs of data, a minimum storage capacity of approximately 600 TBs with an increase of 300 TBs approximately every 6 months would be necessary. The larger TMC in this scenario has approximately three times the data of the smaller in all respects, and consequently requires three times the storage as well (i.e., 1.8 petabytes [PB]).

It is worth noting here that these rough calculations are for storage of all of the raw data from the emerging sources. This clearly points to the need for aggregation and edge processing of the information in the real-time streaming analytics before it is stored. If this were the case, the demand for storage at all regional systems, and the Statewide repository, will be reduced. Significant system resources (random-access memory or RAM and disk) for processing raw data into aggregations and summaries will still be important.

Significant costs can be associated with the acquisition and management of high-performance, PB-scale storage solutions. Many agencies opt to utilize cloud-based solutions, which offer subscription-based models to right-sized and scalable storage services.

DATA SHARING

Impacts on Big Data Tools and Technology Deployment Due to Agency Needs for Data Sharing

Traffic management agencies and TMCs continue to evolve towards more cross-jurisdictional data-sharing functions and coordination with peer and partner agencies through both technical systems and communication methods. As the connected traveler and connected vehicle data sources emerge, the needs to share information with partners will never be greater. As has been true in traffic management for years, travelers do not perceive crossing of jurisdictional boundaries; they simply expect systems, functions, and services to work regardless of the jurisdiction. In particular, when dealing with trajectory data from physical data management, commercial connected vehicles, and connected travelers, starting and ending points of trajectories will invariably fall outside of agency boundaries for a significant portion of trips. Holistic views of systems such as regional emissions models will invariably be made better with regional data sharing. In this section, we discuss some of the issues related to data sharing and big data tools and technologies with respect to several types of institutional relationships, including:

- Multi-regional State DOTs.
- Multi-agency coalitions.
- Joint operations centers.
- Local agencies.

The volume, variety, velocity, and veracity of connected traveler, connected vehicle, and connected infrastructure data will put TSMO agencies firmly into the realm of big data.

5.3 System Platforms

The technology supporting big data and cloud-scale systems continues to evolve, offering a myriad of choices to agencies that may help them meet their ATDM objectives. This section is intended to discuss solutions at the general level and provide suggested practices for selecting services supporting ATDM implementations.

Historically, the primary technology choice for agencies has been whether to host data and systems on-premise, in the cloud, across multiple clouds, or using a hybrid approach. These concepts are discussed on the following page.

- **Cloud Environments –** Service platforms that provide subscription-based services including infrastructure services including compute power, networking, security, and storage, and software services including databases, business applications, internet of things services, ML, etc. The three largest providers of cloud services are Amazon Web Services, Microsoft Azure, and Google Cloud.
- **Premise Environments (Data Center)** – These are owned and operated by the agency or through contract services and typically operate in one or more managed data centers utilizing networking and hardware and software services to run business applications.
- **Hybrid Environments –** These utilize services from two or more connected premise or cloud environments. This also may include premise and cloud services from multiple providers, commonly referred to as multi-cloud.
- **Computational Platforms –** Stacks of integrated software and hardware, and people-useful for high-volume calculation and analytics. These are typically deployed as high-performance computing systems integrated with advanced models providing analytic and research capabilities.

As of 2019, many emerging technologies exist that provide increased flexibility to agencies when selecting which platforms are utilized to deploy their ATDM solutions, including:

- **Multi-cloud replication –** Several methods now exist to provide replication and data consistency across multi-cloud and multi-region data centers.
- **Infrastructure as Code (IAC)** – Some agencies utilize IAC solutions like Terraform, Ansible, Chef, and Puppet to manage and provision data centers through machine-readable definition files instead of hardware configuration or interactive configuration tools. This allows agencies to easily deploy their systems consistently across a variety of cloud and premise platforms, preventing vendor lock-in.
- **Container services –** Like IAC, containers allow systems to be deployed consistently across multiple cloud and premise platforms.

The ability to deploy and migrate systems and data across a variety of platforms allows agencies to build ATDM solutions based on business needs, without the constraint of utilizing a single cloud vendor or technology stack.

CONSIDERATIONS

1. LDM may allow any big data implementation to better align with business practice.
2. To what extent does the master data management tool set meet business practice?
3. Data-level security, including security services such as encryption and fine- or course-grained data record security, may protect data at the record, grouping/table, or database levels. Compliance issues for the data, such as storage of personally identifiable information (PII), may also be considered when selecting ATDM solutions.

4. Infrastructure solution evaluation can be based on data specifications. If done correctly, the LDM process may provide a rich set of specifications that any big data solutions may satisfy. For example, if a large amount of streaming analytics is indicated, an architecture that includes Kafka and Spark may be considered. Large amounts of batch processing may benefit from different technologies like Apache NiFI and HDFS.
5. Federated virtual databases abstract many distributed back-end databases to provide more logical views of the data, such as a business view, analytics view, raw view, etc. This extends the life of the physical data stores because data can be leveraged in different ways, without having to change the structure of the databases and deal with application dependencies.
6. An agency may not have enough trained staff to develop the best solution based on data specifications. Tools are available that allow sophisticated data management with reduced complexity. Many tools provide graphical workflows that allow users to integrate most big data systems without any coding experience required.
7. An iterative approach to implementation may complement evolving agency preferences. Agencies typically evolve as they gain better understanding of data sources and their potential benefits. Generally, a common practice in big data analytics is to start small and identify high-value opportunities.
8. As technology continues to advance, solutions may be obsolete much faster than traditional ITS lifecycles account for. The volume and veracity of data for ATDM may also increase much more quickly than expected. When implementing solutions, agencies may select solutions that can scale horizontally, supporting cloud-scale capacity without requiring any significant change to the current configuration.

5.4 Infrastructure

As stated earlier, deployment elements of a system can be divided into three broad categories: data sources, system platforms, and infrastructure. Data sources and system platforms have been addressed above. Field infrastructure is addressed below.

FIELD INFRASTRUCTURE

ATDM solutions can present unique challenges with regards to field infrastructure design. The structural and geometric design must be evaluated. Specific design features for existing and future field infrastructure may impact the development and deployment of ATDM solutions.

Fixed Objects

Considering fixed objects, the implementation of ATDM solutions may impact the clear zone, either through the installation of additional roadside equipment (e.g., shoulder-mounted signage) or the proximity of moving traffic to fixed objects. For example, fixed objects may be within the clear zone if dynamic shoulder lane use, dynamic lane use, or dynamic lane reversal is in operation, and if drivers leave the roadway, they have a higher chance of striking an object before recovering. Thus, agencies may elect to place new objects outside the clear zone, remove fixed objects if possible, relocate them beyond the clear zone, or shield them with barriers if they are in a place where they are likely to be struck.

Overhead Clearance

Some deployment of ATDM-related solutions may involve the installation of new structures, such as overhead gantries and sign bridges. New structures need to meet existing clearance minimums. These solutions may also have an impact on overhead clearance with existing devices such as sign bridges.

GEOMETRIC DESIGN

Interchange geometrics are important when implementing such ATDM solutions as adaptive dynamic ramp metering, dynamic junction control, or dynamic lane use control. For example, ramp modifications may be necessary to accommodate additional capacity for ramp metering strategies.

Design elements of any ATDM strategy that may have a fundamental impact on the facility should include pavement and signing designs and general design requirements, including controlling criteria and minimum American Association of State Highway and Transportation Officials values. These include but are not limited to:

- Design speed.
- Lane width.
- Shoulder width.
- Horizontal alignment.
- Super-elevation.
- Vertical alignment.
- Grade.
- Stopping sight distance.
- Cross slope.
- Vertical clearance.
- Lateral offset to obstruction.
- Structural capacity of bridges.

5.5 Technology Testing

Technology testing is an integral part of deployment of ATDM. Technology testing is the process of analyzing a system or a component by providing defined inputs and comparing them with the desired outputs. Testing can be divided into two categories: manual testing or automated testing.

Manual testing is, as the name suggests, done manually (i.e., requires human input, analysis, and evaluation). Automated testing is the automated version of manual software testing; using automation helps in avoiding any human errors. The error may occur due to humans getting tired of a repeated process. Automated testing programs will not miss a test by mistake. The automated test program will also provide the means of storing the test results accurately. The results can be automatically fed into a database, which can be used to provide necessary statistics on how an ATDM solution is performing.

Objectives of automated testing are as follows:

- Perform repetitive/tedious tasks to accurately reproduce tests.
- Validate requirements and functionality at various levels.
- Simulate multiple users exercising system functionality.
- Execute more tests in a short amount of time.
- Reduce test team head count.

5.6 Public Outreach

Data privacy and cybersecurity are of vital concern to both an implementing agency and the general public. A balance between public outreach and security is not unique to the transportation domain.

For transportation systems, the standard for analysis of security for application information flows is based on Federal Information Processing Standard (FIPS) 199, device class security controls are based on FIPS 200 and National Institute of Standards and Technology Special Publication 800-53. Regarding data privacy, The Privacy Act of 1974 protects the personal information the Federal Government collects and regulates how it can disclose, share, provide access to, and keep the personal information that it collects. The discussion of privacy might include the following: a stated privacy policy, clear delineation for handling PII, a statement of information collected, and bounds of data use including shared information cookies and other tracking devices.

To keep the public informed, note the clarity for the need for public outreach in the 'Cybersecurity 2020 Census' statement":

> "We will maintain the public's trust and confidence by protecting their data and keeping them informed." [48]
>
> https://www2.census.gov/cac/sac/meetings/2018-12/smith-cybersecurity-public-trust.pdf

CHAPTER 6. OPERATIONS AND MAINTENANCE CONSIDERATIONS

This chapter provides insight into the considerations for operation and maintenance (O&M) as it relates to emerging technologies and data sources. Routine O&M maintenance will be different due to the very nature of these technologies as will other areas such as cybersecurity and data privacy, performance monitoring and maintenance, enforcement, O&M costs, and future proofing.

6.1 Routine Operations and Maintenance Issues

Once the new and/or enhanced ATDM solutions go online, there are a host of O&M issues to deal with. Some items for consideration include performance monitoring, routine maintenance, enforcement, and costs. Moreover, many of the emerging technologies and data sources discussed in this Reference require critical O&M considerations.

Some investigations of active transportation and demand management (ATDM) O&M issues have already been published. One example is the *ATM Implementation and Operations Guide*, which provides a full chapter on O&M.[17, 37] Some O&M principles discussed here (e.g., necessary data, levels of automation, common performance measures, typical O&M costs, post-project evaluation) are likely relevant to the newer technologies and to the broader ATDM scope. The *ATDM Lessons Learned* report described numerous real-world implementations, some of which cited maintenance as a significant dis-benefit.[62] The technical brief on *Data Needs for ATDM* [11] discussed the data needs for monitoring and evaluation. The brief says that, although ATDM operations objectives are inextricably tied to performance measures (e.g., travel time, delay, planning time index), supplementary data should also be collected to understand the impacts of exogenous factors (e.g., price of fuel, unemployment rates, other highway improvements, work zones). The *Guide for Highway Capacity and Operations Analysis of ATDM Strategies: Analysis of Operational Strategies under Varying Demand and Capacity Conditions* [23] highlights the importance of non-recurring event data and of forecasting the various percentile outcomes (e.g., expected 80th and 95th percentile worst performance).

CYBERSECURITY AND DATA PRIVACY

Some of the emerging technologies and data sources present some unique cybersecurity and privacy concerns. Many of today's ATDM systems are relatively "closed" from the standpoint that they communicate with sensors, devices, and external systems that are on the agencies' private network. Some of these newer technologies and data sources are connected with outside "uncontrolled systems" and in their nature may have some data privacy considerations. The particular ones that should be noted include:

- Crowdsourced data feeds.
- Cloud computing.
- Big data.
- Connected and autonomous vehicle data.

- Video analytics.
- Bluetooth/WiFi sensors.
- Internet of things (IoT).
- Global positioning system (GPS) and automated vehicle location (AVL) data.
- Mobile sensors.

For enhancing ATDM through emerging technologies and data sources, many of the primary O&M considerations involve management and security of data. The FHWA Reliability Data Guide's section on data ownership and maintenance presented a sample list of fundamental considerations likely to govern O&M levels of effort and expense: [30]

- Who will pay to collect, store, and share the data?
- Who (if anyone) can sell the data, and to whom may it be sold?
- Are there any privacy issues in the data that must be addressed (e.g., MAC addresses stored from collection of Bluetooth sensor data)?
- Who is allowed to access the data, and what data may they access (all of it? only a subset?)?
- What purposes are the data allowed to be used for (e.g., if they are collected for analysis purposes only, could they also be used for enforcement?)?
- What data use agreements are in place and must be adhered to use the data (e.g., not allowed to store or disseminate information)?

CAVs are a key quadrant of emerging technology that gain a lot of attention as it relates to cybersecurity (access to a vehicles bus) and data privacy (data that can be potentially used to track vehicle locations). Some ATDM solutions (e.g., multi-modal intelligent signal systems, integrated dynamic transit operation) are specifically designed to exploit CAV technology. Archiving, documentation, and analysis of the resulting data may be critical to the success of such deployments. A presentation entitled "Sharing Connected Vehicle Data on the Research Data Exchange (RDE)" addressed some of the challenges and opportunities associated with high-volume multi-source data from CAV, connected travelers with mobile devices, and other sources.[43] Figure 23 illustrates some of the O&M activities needed to enable CAV benefits.

Source: FHWA

Figure 23. Screenshot. Linkage of connected and automated vehicle goals and operations and management issues.

Data security is a key component of data archiving. Vandervalk et al. suggest that working copies of databases maintained on primary servers be replicated in compressed formats at remote sites.(51) These daily backups, which do not reflect a binding legal requirement, ensure that the archive service can be rapidly returned to operation with no significant loss of data if a copy of the database is lost. Both the primary database server and the backup storage are located in climate-controlled machine rooms with uninterruptible power supplies and generator backup power, preventing data loss or gaps in data availability due to power outages. The working copy of the database is stored on a redundant array of independent disk devices, providing error detection, redundancy, and the ability to rebuild missing data upon device failures. Finally, hardware maintenance and security updates are provided for all computer systems by experienced systems administration personnel.

The *Real-Time Data Capture and Management State of the Practice Assessment and Innovations Scan* addressed issues related to data capture, data management, archiving, and sharing collected data to encourage collaboration, research, and operational development and improvement.(44) The scan covers five industries: aviation, freight logistics, internet search engines, rail transit systems, and transportation management systems. The scan documented best practices in several areas which are outlined here for reference. Please note that the best practices are strictly voluntary and they are not legally binding. The scan documented the following best practices for access, security, and privacy:

- Generally, the holder of the data controls access to them. Within the transportation and logistics community, this access is carefully controlled.
- There are systems in place that ensure that data can be accessed only by the intended people and only to the degree that they need it. The type of data used by the transportation and logistics industry makes it extremely sensitive, with disastrous consequences for business if accessed by persons with malicious intentions.
- Usually, data access is password-protected, and the following is true:
  - Because data generated within the logistics systems are often financial, strong encryption is placed on such data when they are sent.
  - However, several applications can retrieve aircraft and vessel tracking data, often with other identifying information. The security clearance or password protection to access data through these applications is often minimal.
- The protection of data sources is extremely important. In the search engine industry, it is so heavily protected that there is not even disclosure of how exactly it is protected.

The scan documented the following best practices for data storage and backup:

- Frequent backups and off-site storage are typical.
- Preventative maintenance should be performed regularly.
- Careful consideration should be devoted to determining how much and for how long data should be stored. In aviation, for instance, data are kept for a relatively short timeframe because the need is for real-time rather than historical information. At the same time, data can be available for revision if there is an incident to investigate.

The scan documented the following best practices for O&M:

- Deployment should be started on a reasonable scale, such as implementing in a small geographical area or using easily manageable data.
- Multiple servers should be used to distribute real-time loads. Several technologies enable this load distribution.
- It is important to consider determining the needed resolution or granularity of the data. This may vary depending on the context and use of the data. Specific examples include the following:
  - In the logistics and retail industries, inventory data are refreshed every minute in several stores. This is used to support restocking and also to monitor trends.
  - In the search engine industry, data generally go through a 24-hour refresh cycle, staying fixed between cycles.
  - In the aviation field, data are mostly retrieved as fast as possible to enable incident prevention.
- It is necessary to determine what is critical to communicate and what is not. For instance, railroad and airline alert systems only collect the necessary data that can alert an operator of a particular problem.

The scan documented the following best practice for critical failures:

- A common issue is that correcting a problem is often dependent on a single person, meaning its solution depends on the person's availability. It is, therefore, important to have staff available around the clock to solve potentially catastrophic failures. The higher labor cost is a necessary expense if the system needs to be highly available at all times.

PERFORMANCE MONITORING AND MAINTENANCE

As discussed in the *ATM Implementation and Operations Guide*, performance monitoring is an integral part of the active management cycle, which was illustrated in chapter 1.[17, 37] Performance monitoring is an ongoing internal process where system conditions and performance are examined and evaluated through data collected through interfaces with devices/equipment installed in the field as well as data feeds such as probe or crowdsourced data. Performance monitoring provides the data needed in the decision-making process. Deployment agencies use data and performance monitoring during strategy activation. Activations typically fall into one of two types of processes, automated systems and manual systems, which vary greatly in the strategy activation thresholds used. In some cases, a hybrid automated-manual process is used.

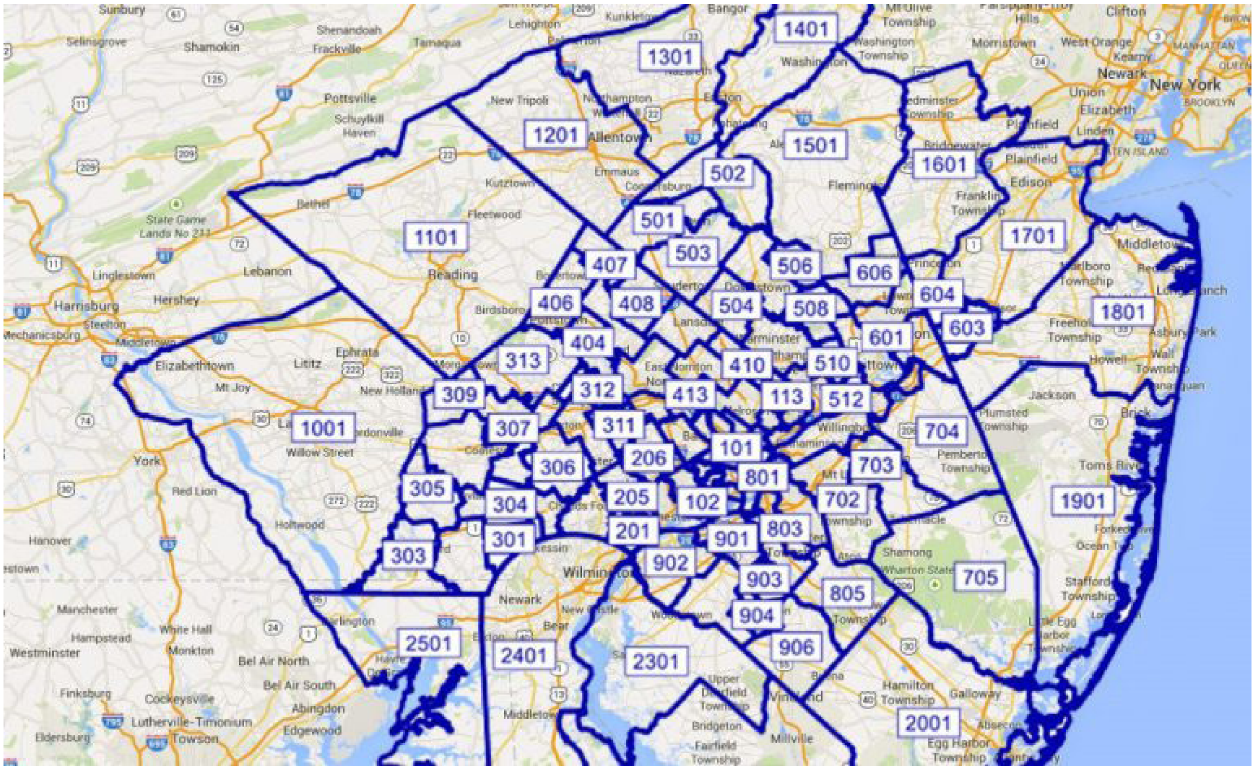
ATDM deployments are often part of an agency's overall transportation management system, which is a complex, integrated amalgamation of hardware, technologies, and processes. System maintenance includes replacing worn components, installing updated hardware and software, tuning the systems, and anticipating and correcting potential problems and deficiencies. Maintenance includes the development and implementation of action plans for responding quickly, efficiently, and orderly to systemic failures, as well as having infrastructure and procedures for measuring and monitoring maintenance activities. An agency's maintenance strategy can dictate system design and must be considered in the planning phase to ensure that it will have the personnel or financial resources to adequately maintain the ATDM solution.

The ATM *Implementation Guide* provides more specificity on performance monitoring for specific solutions.[17, 37] For example, the guide lists a of sample agencies who implemented automated thresholds for ramp metering activation. Such thresholds were typically a combination of mainline occupancy, mainline volume, ramp queue length, and/or ramp storage length. Threshold values may be updated periodically (i.e., monthly, quarterly, or annually) based on continued assessments of system performance. Because the effectiveness of short-term and long-term performance monitoring depends on the quality of data collected, having access to quality data is an important element of performance monitoring. Emerging technologies and data sources can augment performance monitoring in active traffic management (ATM), active demand management (ADM), and active parking management (APM).

Active Traffic Management

Many strategies activate at specific traffic congestion levels to prevent, mitigate, or delay the onset of traffic bottlenecks. To accomplish this, performance monitoring is critical to determining when strategies should activate. Some predictive strategies employ combinations of historical and real-time data. Bayesian models use real-time data to improve the accuracy of predictions based on historical data. Machine learning (ML) methods are able to fine-tune and improve these prediction algorithms over time. Beyond monitoring traditional metrics such as flows, speeds, and densities, inclusion of non-recurring event data (e.g., weather, incidents) can help to explain performance and improve predictions. In summary, ATM performance monitoring can be augmented through (1) fusion of historical and real-time data (e.g., Bayesian methods), (2) explicit use of non-recurring event data (e.g., weather, incidents), and (3) ML.

To augment the ATM solutions as described above, emerging technologies can help to improve both the quality and quantity of available data, especially when compared and/or combined with more traditional forms of data. For example, probe data are now used extensively to obtain traffic performance metrics. Social media provides a source of incident data.[53] Dynamic message signs (DMSs) can display optimized sets of driver information based on enhanced data sets and learning methods. Some urban data sets, including both traditional traffic sensors (e.g., loops, cameras) and cutting-edge sensors (e.g., Bluetooth, GPS probe, parking), have been archived for a decade. These rich data sets allow learning of traveler behavior and in-depth understanding of non-recurrent traffic. They can be applied directly to predict traffic impact of planned and unplanned incidents and provide real-time decision making for traffic operations.[55] Figure 24 illustrates an example of this ATM augmented by emerging technologies.



Source: © Wei Ma, Pinchao Zhang and Sean Qian (2016)

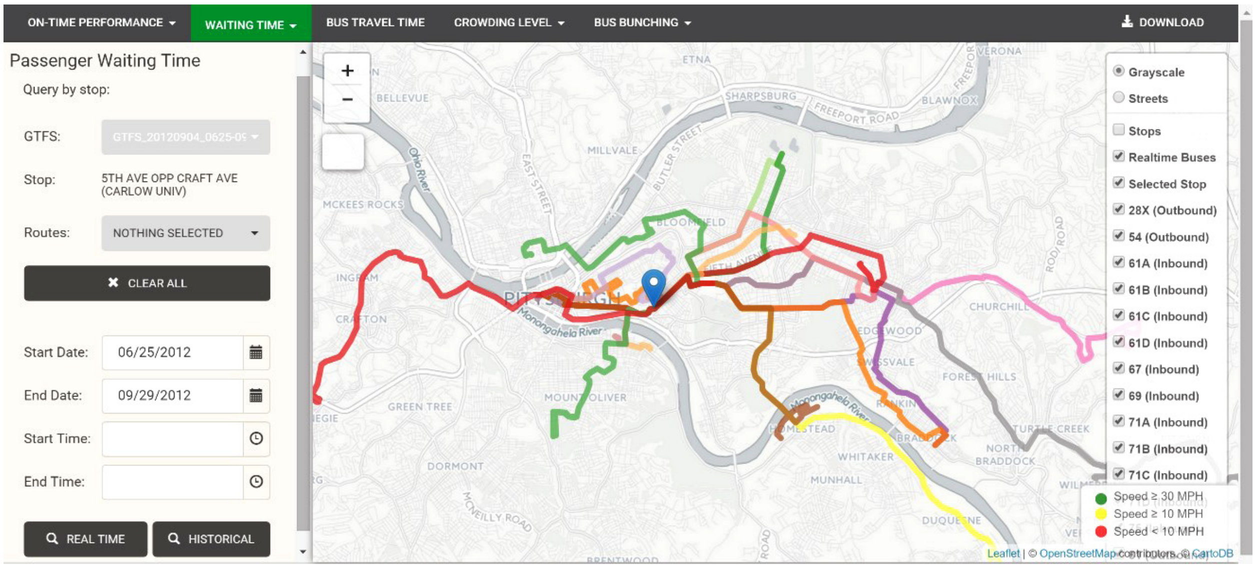
Figure 24. Map. Dynamic network analysis and real-time traffic management for the Philadelphia Metropolitan Area.

Regarding O&M issues for ATM, quality control has been a concern for probe data. Agencies may wish to monitor the proportion of missing data over time within probe data sets. Along surface arterials, accuracy of probe data may be compromised by the proximity and influence of traffic signals. Also, the proportion of vehicles surveyed within probe datasets changes over time and may become unacceptably low in some areas. Beyond probe data, weather and incident data may be less accurate on certain roadway segments. In summary, cutting-edge sensors and learning algorithms may require annual audits, calibration, and repairs, just as traditional sensors would.

Active Demand Management

Under ADM, traveler choices can be influenced by access to the right information. In many cases, this information can be improved and/or optimized by emerging technologies and data. In the Stanford CAPRI study described later in this Reference,[(13)] commuters were successfully incentivized to re-distribute their departure times in ways that were far more efficient for the overall surface network. In addition to an innovative incentives structure, the program used emerging technologies such as radio frequency identification (RFID) sensing, smartphone applications, and social media. In theory, the traffic flow incentives and monetary awards could be further optimized by a fusion of ML and performance monitoring.

In another example, automatic passenger counters (APC) and AVL data have been used to optimize the supply and demand for public transit. The essential idea is to fully utilize the big data in public transit to provide travelers fine-grained, customizable information regarding transit service performance (efficiency, reliability, and quality). This information can be distributed via DMSs at transit stops or on smartphone applications. An example of such information is shown in figure 25. Moreover, transit providers can monitor day-to-day transit service, and can monitor how transit users respond to information. They can develop a better understanding of travelers' preferences on efficiency, reliability, and quality of transit service, as well as their modal choices. Big data and data-driven behavioral models facilitate agencies' decision making (such as scheduling). Effective information provision, along with data-driven scheduling, holds great potential to improve the service performance and travelers' riding experience.



© Pi et al (2017)

Figure 25. Screenshot. Transit passenger wait time. (52)

Regarding O&M issues, RFID, APC, and DMS devices may require physical maintenance and repairs. Similarly, social media data and smartphone applications software may require periodic technical support and software updates. For example, if a social media vendor releases a software update that modifies its input-output format, any data mining tool used to access the social media data will require corresponding updates and software patches.

Active Parking Management

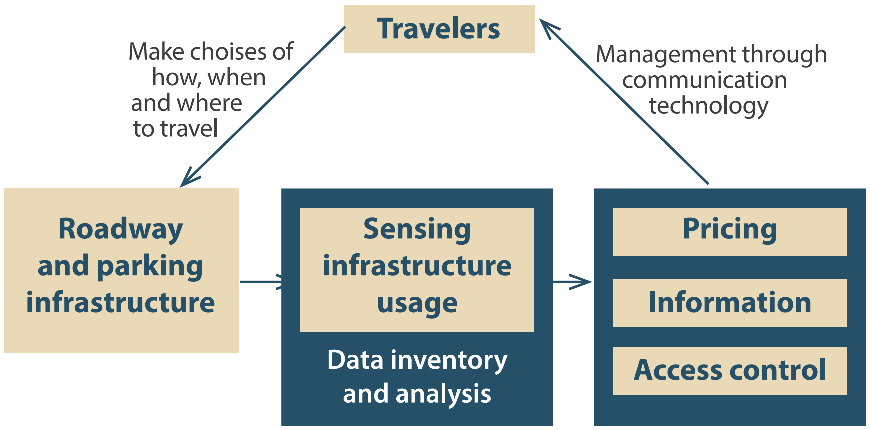
Parking can consume a significant amount of the trip costs (time and money) in urban travel. As such, it can considerably influence travelers' choices of modes, locations, and time of travel. Advanced performance monitoring via smart sensors, wireless communication, social media, parking meter transaction data, and big data analytics offers a unique opportunity to tap parking's influence on travel to make the transportation system more efficient, cleaner, and more resilient.(56, 57, and 58) Essentially, these emerging technologies and data sources may facilitate:

a) Changing day-to-day behavior of all commuters through day-to-day travel experience and/or online information systems.

b) Changing travel behavior of a fraction of adaptive travelers on the fly who are aware of time-of-day parking information and comply to the recommendations.

c) Influencing market prices of privately owned parking areas through a competitive parking market.

Figure 26 illustrates the APM-centric active management cycle.



Source: FHWA

Figure 26. Diagram. Enhancement of active parking management using technologies and data.

Regarding O&M issues for APM, the quantity and location of available parking spots is constantly changing. Any cyber-physical system based on parking data will require constant updates. Social media platforms and parking meter transaction data are subject to software updates. Wireless communication technologies are not static. To combat these instabilities, there is a need for human audits, post-deployment monitoring, and dedicated O&M budgets. ML, which represents an automated form of audits, is also highly advisable to complement and support any human audits. Depending on the success of the automated monitoring system, the expenses associated with having humans in the loop may dissipate over time as the human effort decreases accordingly.

ENFORCEMENT

Law enforcement opportunities and capabilities are evolving along with the new technologies. This has ramifications for ATM and APM. The typical ADM applications (e.g., dynamic ridesharing, on-demand transit, dynamic pricing, predictive traveler information) may not have significant enforcement concerns.

One prominent issue is traffic violations involving CAVs. These vehicles could potentially be programmed to avoid speed limit violations, parking violations, red light running, and usage of closed lanes. An increasing market penetration rate of such vehicles could significantly reduce the burden of law enforcement. However, there are many privacy issues associated with CAVs. The driving public will not necessarily accept unfettered control of their driving behaviors and identification of their whereabouts. Therefore, the enforcement impact of CAV technology remains uncertain.

Active Traffic Management

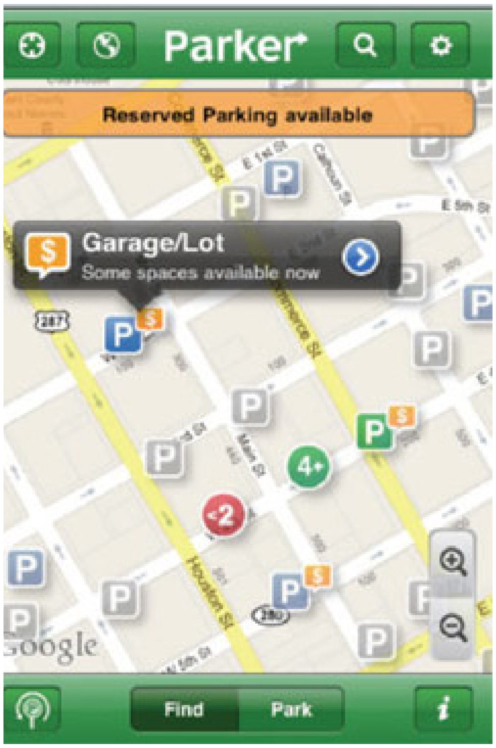
Adaptive ramp metering and traffic signal control strategies can now be deployed on freeways and arterials. Red light running and speed limit violations are two enforcement concerns related to traffic signals, regardless of deployment location. While CAVs may help to prevent such violations, automated traffic signal performance measures may reveal such violations from conventional vehicles and drivers. Automated vehicle or license plate identification may streamline the enforcement process.

Two other ATM solutions affect which lanes drivers may use. Dynamic lane and shoulder use allow for temporary opening or closing of travel lanes in response to increasing congestion or incidents. Dynamic junction control prioritizes the critical roadway to minimize the impact of merging and diverging maneuvers. In these cases, illegal use of a closed lane becomes an enforcement issue. While CAVs may help to prevent such violations, automated vehicle or license plate identification may again streamline the enforcement process with conventional drivers. The automated identification may be more technologically challenging along lengthy (i.e., up to many miles long) dynamic lanes or shoulders, on which the violating vehicle location is much less certain than at traffic signal stop-lines or stop-bars.

Finally, dynamic speed limits may change based on road, traffic, and weather conditions. Speed limit violations are possible. A combination of technologies is needed to identify vehicle speeds (not necessarily in real-time) and identify the violating vehicles or drivers. Again, the frequency of speed limit violations may potentially be reduced by CAV technology.

Active Parking Management

APM solutions can dynamically modify parking spot permissions, prices, and availability. Smartphone applications (e.g., figure 27) that facilitate parking spot payments from remote locations should interface with any APM solutions that may be in effect to prevent unnecessary violations. Automated vehicle or license plate identification may help to reduce law enforcement labor and costs. The frequency of parking violations may potentially be reduced by CAV technology, which can be designed to avoid such violations. However, when APM solutions are in effect, infrastructure-to-vehicle communication may be needed for CAVs to avoid such violations.



Source: ExpressPark™

Figure 27. Screenshot. Smartphone parking application.

COSTS ASSOCIATED WITH ACTIVE TRAFFIC MANAGEMENT

Costs associated with ATM merit consideration long before implementation. Cost data are available through various tools and resources (i.e., TSMO Benefit Cost Compendium,[60] Intelligent Transportation System [ITS] Joint Program Office [JPO] online database,[47, 61, and 62] Tool for Operations Benefit Cost Analysis, Operations Benefit/Cost Analysis Desk Reference to support Tool for Operations Benefit Cost Analysis).[27] Some of the major costs include capital investment into infrastructure, technology, long-term operations, maintenance, and upgrades of the system over time. Usually, the Federal Government provides funding for ATM solutions and projects for both initial construction and ongoing costs. Various Federal Government initiatives provide opportunities for funding ATM solutions individually or along with other activities or projects. State and local level funding are also available. Some ITS infrastructure installations and integrations that may qualify for Federal funds are listed below:

- Emergency services.
- Incident management systems.
- Electronic toll collection systems.
- Electronic fare payment systems.
- Freeway management systems.
- Transit management systems.
- Traffic signal control.
- Regional ITS architecture development.

Emerging ATM technologies also require hardware, software, and software integration. Therefore, the long-term support of software, including routine checks and modifications, is a consideration. The integration of CAVs into ATDM solutions will involve implementing advanced infrastructure, which needs to be properly maintained for a longer lifespan.

6.2 Future Proofing

A big challenge with technology systems is how to keep them current so they will not need to be constantly updated (often at high costs) as technologies advance. For operational systems such as ATDM, these systems do not need to be quickly obsolete and/or require a replacement shortly after the system is installed. It is difficult in today's quickly moving world of evolving technology to have systems such as these to be truly future-proof, but there are steps that can be taken to help ease the impact of evolving technology. These steps, which are not required, include the following:

- **Perform technology maturity and evolution assessment before implementing a new technology or data source.** For example, if a new technology is being investigated, key questions to ask are: (1) how many companies or vendors are doing it, (2) how prevalent do the technology industry experts see the future vision of the technology, and (3) what are the size of the companies and systems that use it, etc. If there is an interesting new technology, but only one of two firms sell the product, this may be a flag for its long-term longevity of maturity.

- **Select technology options that offer flexibility, scalability, and consistency.** For example, cloud computing is viewed by many as very future-proof because upgrades and updates can be invisible to the user and the system scales seamlessly. These types of environments will keep up with current technology.
- **After implementation, perform regular change control meetings, typically with a change control board.** This will allow agencies to predict future changes and plan for them in advance. For example, a software product vendor may announce that the current version of the product is being discontinued in a year and an upgrade will be required. This will allow the impacted agency to assess the effect including costs and plan in advance. It will also allow agencies to potentially look at alternate replacements if the upgrade path is too disruptive or costly.
- **Build a future-proof information technology (IT) plan.** A future-proof IT plan includes taking into consideration future IT trends, changes in material acquisitions, changing price models, new and emerging options for system upgrades, and which upgrades may be the most efficient.
- **Create continuing education programs that allow staff to constantly learn about new technologies and trends so they can be brought forward as part of future-proofing exercises.**
- **Work to have a good working relationship between transportation departments, transportation operations and IT departments.** Through working together on items like continuous technology improvement plans, the pitfalls of technology obsolescence can be avoided.

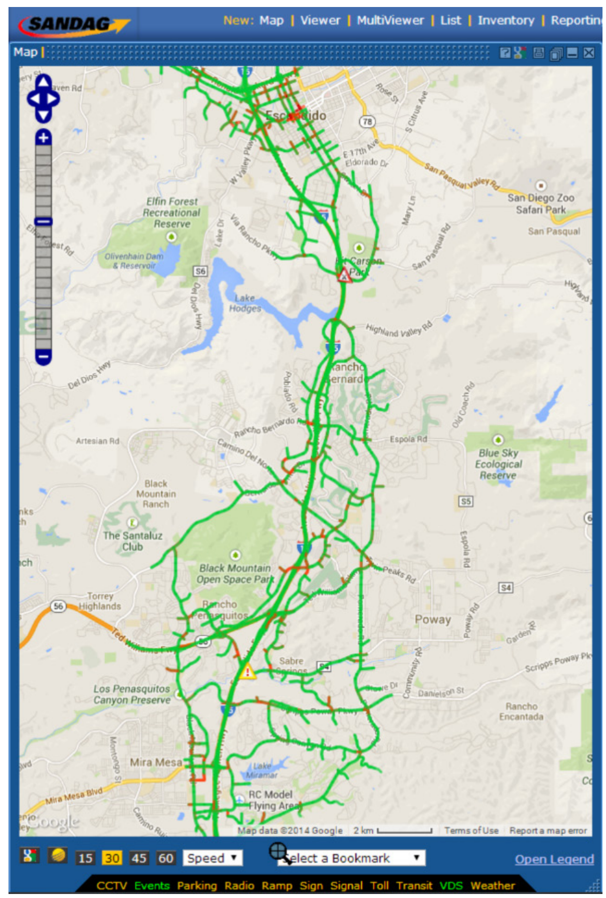
CHAPTER 7. CASE STUDIES

This chapter describes three case studies that exemplify the use of active transportation and demand management (ATDM) solutions in conjunction with emerging technologies and data sources. The San Diego and Netherlands case studies are implementations of active traffic management (ATM). The Stanford case study demonstrates both active demand management (ADM) and active parking management (APM). Whereas the beginning of each case study summarizes the relevant emerging data and technologies, the end of each case study speculates as to how the relevant emerging data and technologies could be further leveraged in the future.

SAN DIEGO INTEGRATED CORRIDOR MANAGEMENT SYSTEM

ATM and ADM Approach: ATM and ADM.
Emerging Technologies and Data Currently in Use: Artificial intelligence (AI), decision support systems (DSS), real-time microsimulation, and on-line traffic prediction.

The Interstate (I-) 15 integrated corridor management system (ICMS) project focuses on a 20-mile stretch of I-15 between State Route (SR) 163 in San Diego and SR 78 in the City of Escondido.[45] The San Diego I-15 integrated corridor management (ICM) corridor is a congested north-south interstate corridor. It forms the primary artery for the movement of commuters, goods, and services from northern San Diego County to downtown San Diego. This project aims to operate and manage individual transport systems as a unified corridor including the highway network, toll lanes, surrounding arterials, and public transport network in the area. The San Diego Association of Governments (SANDAG) is leading the project and works alongside the U.S. Department of Transportation (USDOT), Caltrans, the Metropolitan Transit System, and the North County Transit District. SANDAG also works with the Cities of Escondido, Poway, and San Diego, with Delcan Corporation serving as the project integrator.



Source: SANDAG

Figure 28. Screenshot. San Diego Association of Governments project area map of Interstate 15.

SANDAG's vision is to develop a high-fidelity analytical platform to test new and evolving concepts with high resolution, and to mimic real-world operations in a simulation environment. The I-15 ICMS project introduces 'smart' traffic management technologies and concepts never used before in the United States. The project's pioneering

DSS uses a number of technology solutions such as network traffic prediction, on-line microsimulation analysis, and real-time response strategy assessment, to give system managers comprehensive awareness of the current and predicted future performance of the entire corridor. Core to the ICM solution is the ability to forecast and simulate congestion and capacity imbalances in real-time or near-real-time.

The DSS allows continuous predictions every 5 minutes to monitor and anticipate congestion hot spots. It can launch evaluations of available strategies to select the best response. This helps to minimize congestion and improve prediction of journey times for both drivers and users of public transport. Rather than reacting to traffic conditions, managers can anticipate problems and take preventative action using ICM strategies such as:

- Responsive traffic light synchronization.
- Coordinated ramp metering or bus priority on arterials.

The I-15 ICMS is designed to optimize capacity and efficiency, reducing delays and obtaining more reliable journey times without the need for investment in additional infrastructure (namely, more lanes for private traffic). The multimodal DSS integrates two tools:

- The Delcan Intelligent NETworks ATMS.
- Aimsun Live.

The Delcan Intelligent NETworks ATMS is used for field device monitoring and control, center-to-center data fusion, event management, and response plan generation. Aimsun Live uses live data feeds and simulations to dynamically forecast traffic conditions based on the current state of the network, which helps system managers evaluate incident response or congestion management strategies.

The I-15 ICMS is one of the first working examples of management integrated with prediction, which allows the anticipatory administration of an area that is very complex in terms of transport and mobility.

The ICM network is being used to assess the role that predictions play within ATDM, incorporation of new functionality to the corridor (speed harmonization and dynamic merge control) and the sensitivity of prediction duration on DSS effectiveness. SANDAG expects the ICM project to help with:

- Implementing multimodal and smart growth principles.
- Improving safety throughout the corridor.
- Increasing traveler information mechanisms, institutional partnerships, and networked transportation systems, both during recurrent and non-recurrent conditions.

According to SANDAG's ICM Concept of Operations (ConOps) document, successful implementation of the ICMS and concepts requires a proactive, strategic, and collaborative approach to public and private-sector stakeholder partnerships, along with a history of successful joint operation initiatives, both of which have been achieved under the institutional umbrella of SANDAG.[45] A virtual corridor transportation management center (VCTMC) allows for coordination among multiple agencies on multiple levels for data collection and processing, data sharing, and decision support based on workflow and on an expansion of available information. Other critical assets for the corridor include a real-time advanced travel information system, intermodal transportation management system,[45] regional integrated workstations in city traffic engineering departments, performance management system, region-wide adoption of a common traffic signal control platform, managed lanes, and bus rapid transit with direct access ramps. Beyond this, the ConOps identified the following implementation issues:

- **Technical Issues** – Data archiving and accessibility for future analyses; modifying/updating San Diego regional intelligent transportation system (ITS) architecture to bring it into alignment with the I-15 ICMS concept; using a regional transit fare system across multiple transit service providers; expanding functionality for 511; and ensuring quality, frequency, and accuracy of information.
- **Operational Issues** – Enhancing transit capacity in response to planned events and major incidents; implementing bus signal priority for transit on arterials; coordinating different operating systems across agencies to work together (e.g., I-15 freeway on-ramp metering signals with adjacent arterial traffic signals); and fully integrating commercial vehicle operations into the I-15 ICMS concept.
- **Institutional Issues –** Establishing policies and arrangements with private entities; compatibility of VCTMC responsibilities for I-15 ICMS corridor stakeholders with their conventional responsibilities; expanding organizational stakeholders beyond those that are only transportation-focused; and enhancing the level of inter-organizational coordination and integration among corridor stakeholders.

Hypothetical Uses of Emerging Technologies and Data

- Machine learning (ML) to refine the ICMS impact on traffic flow performance measures.

STANFORD UNIVERSITY'S CONGESTION AND PARKING RELIEF INCENTIVES STUDY

ATDM Approach: ATM and Active Demand Management (ADM) through Incentives.
Emerging Technologies and Data Currently in Use: Radio frequency identification (RFID) sensing, smartphone applications, and social media.

One of the largest employers in the San Francisco Bay Area, Stanford University signed a General Use Permit with the County of Santa Clara that requires the university to manage its transportation impacts under a "no net new commute trips" standard: The amount of traffic during peak hours must not increase by more than 1 percent during the morning and afternoon peak hours (based on traffic count data from 2000). By 2012, while existing measures had been effective in reducing the total number of commuters who drive alone, they did not directly address peak-hour commuters, whose numbers were increasing.

In an effort to address this imbalance, the university, with a $3 million grant from the FHWA Value Pricing Pilot Program, launched the Congestion and Parking Relief Incentives (CAPRI) program,[13] which ran from April 2012 through September 2014. Its goal was focused on shifting driver commutes away from peak hours but was expanded in 2013 to incentivize walking and bicycling commutes. The approach behind the project is based on the understanding that "congestion is a 10 percent phenomenon." [33] In other words, a small reduction in demand can lead to a significant drop in congestion. By targeting peak-period commutes, a corresponding decrease in peak-period congestion around the university could be achieved.

Sleeping in might never feel better. To lower traffic congestion and pollution, a new program seeks to get Stanford drivers to avoid arriving and departing the campus during peak hours. Professor Balaji Prabhakar aims to deliver social benefits at low cost using people's penchant for a chance at a bigger payout over a predetermined small reward.

In addition, rather than penalizing undesirable behavior, such as increasing the cost of transit during peak periods, the CAPRI project approach was designed to incentivize decongestion by using "carrots" to influence driver behavior. This methodology leverages game theory, in which games with low stakes see players become more risk-seeking, resulting in greater user responsiveness achieved by paying out random "chunky" rewards rather than small, deterministic payments. CAPRI built on the incentives used in earlier programs, as well as Steptacular and Insinc programs in terms of both behavioral interventions as well as technological elements.[35] Another benefit of a system like CAPRI is that it does not require legislation.

In April 2012, Stanford University parking permit holders who parked inside the "congestion cordon" were invited to participate in the program. Those who enrolled were given passive radio-frequency identification tags to place on their windshield. Entries and exits were tracked by sensing devices at 10 main access points on the Stanford campus during the 7–10 a.m. and 4–7 p.m. periods each weekday, with peak hours defined as 8–9 a.m. and 5–6 p.m. (figure 29). For each automobile detected by the sensors during the off-peak shoulder hours (i.e., 7–8 a.m. and 9–10 a.m. and 4–5 p.m. and 6–7 p.m.), the participant was awarded 10 points.[54]

Additionally, CAPRI assigned each participant a "boost day," or a day on which their off-peak trip earned them 30 points. Beginning in May 2013, the project was expanded to incentivize walkers and bicyclists by awarding them between 10 and 25 points, depending on the length of their commutes. Walking and biking activity was monitored using the "My Beats" smartphone application developed for this project.

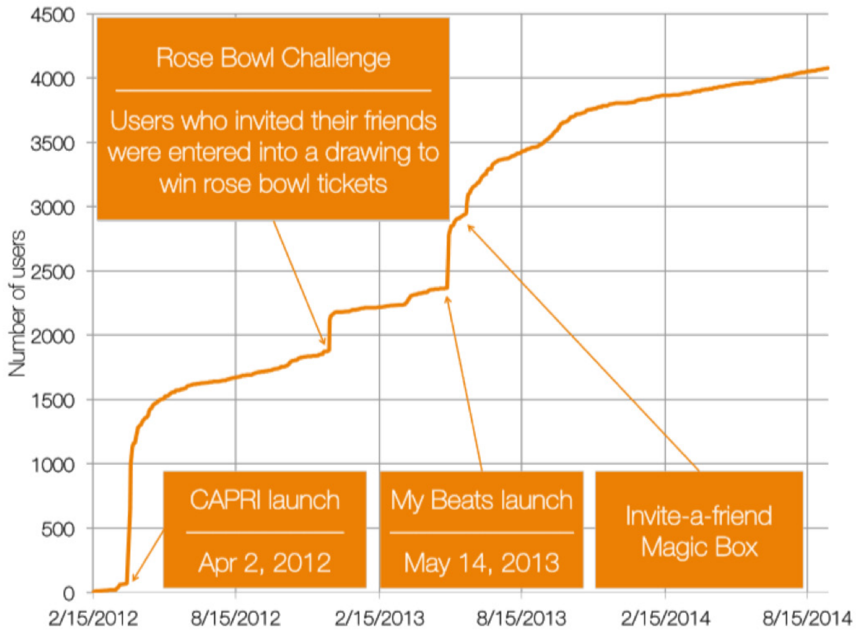
Participants were incentivized by receiving points for commutes during off-peak periods and non-motorized commutes. These points could be redeemed in one of two ways:

1. Deterministically, by trading 100 points for $1 (or a full week's worth of off-peak trip points).
2. Randomly, by playing a "chutes-and-ladders" -type game using their points on the CAPRI website.

Source: Golden 2012

Figure 29. Photograph. Radio frequency identification scanners installed on Stanford University campus for the CAPRI project. (33)

The game gave cash rewards ranging from $1–$50. The follow-on study of the project found that 87.3 percent of the participants used the random rewards option, validating the theory behind the project. Notably, because participants were allowed to change the manner of redeeming rewards, 13.2 percent of the participants ended up switching from the deterministic option to the random option at some point during the program (figure 30).



Source: https://forum.stanford.edu/ events/posterslides/CapriCongestionandParkingReliefIncentives.pdf.

Figure 30. Chart. Number of CAPRI registrants over time. (13)

CAPRI also tapped into basic human traits such as the desire to improve one's social status, the desire to connect with friends, and the desire to feel understood to increase the popularity, engagement, and behavior shift among the participants. This was accomplished through a rewards system that encouraged the desired behaviors and made them fun:

- **Status system** - Participants began at the bronze level and were able to advance through silver, gold, and platinum levels based on the number of off-peak shoulder hour trips they made on a weekly basis. At the silver, gold, and platinum levels, failure to make the number of off-peak shoulder hour trips required for that status level resulted in a degrading of the status by one level. Recognizing that status is only worth something if it is associated with a privilege, CAPRI gave participants with higher status higher odds of winning rewards in the game, and higher-valued rewards were only available at the higher status levels. For example, a $50 reward was only available at the Platinum level.
- **Friends** - Leveraging the popularity of social media, CAPRI participants were allowed to invite friends who were eligible to participate in CAPRI to join the program as well as to connect with their friends on the CAPRI portal. Participants could see their friends' recent updates, including status upgrades, any cash awards won, etc. This feature provided a basis for social influence to spread.
- **Magic Box** - Based on a participant's tracked preference for commuting off-peak, this incentive offered weekly personalized opportunities to gain additional points through a tab in a commuter's portal called "Magic Box." For example, filling out an optional survey might garner the user an additional 200 bonus points.
- **Trendjacking** - Because Stanford University participates in numerous high-profile sporting events, CAPRI offered tickets to some of these events and used them to incentivize behavior shift or increase enrollment.

Participants

Over the 30-month study period, 4,057 Stanford affiliates completed the registration process; this includes 3,082 car commuters and 975 biking/walking commuters. These car commuters included about 30 percent of the 10,290 car commuters in Stanford who were ever eligible to participate.

Outcomes

A post-project study identified the following results of the CAPRI program:

- **CAPRI users avoided peak hours.** For CAPRI participants, the peak-hour trip ratio is only 30.1 percent in the morning and 32.4 percent in the evening, which is a 21.2 percent and a 13.1 percent reduction, respectively, from the Stanford-wide traffic.
- **CAPRI users responded to incentives.** The commute density for CAPRI participants peaks next to (but just outside) the peak hours. Also, CAPRI users preferred commuting during the hour before the peak hour as compared to the hour after the peak hour.
- **CAPRI rewards had a direct effect on participants' commute time**. Results of the study show that participants will shift their commute time away from peak hours when receiving rewards in the recent past.
  - Early commuters who have friends winning rewards in the past week travel around 1.5 minutes earlier. Early commuters also advance their commutes by an additional minute on their boost days to ensure receiving bonus award points.
  - Late users who won rewards in the past week shift about 3 minutes later in morning and afternoon (non-peak) commutes.

"The program most certainly helped the university stay below the trip limit," said Brodie Hamilton, director of Stanford's Parking and Transportation Services, which helped to administer the project. "Data show CAPRI participants are to a large extent avoiding the peak travel times."

Since the conclusion of the CAPRI program, Stanford University developed and is currently hosting a "Commute Club" through its Parking and Transportation Services program. This program offers a variety of incentives to the more than 10,000 members who commute to and from the university. Incentives include up to $300 a year in "Clean Air Cash" or carpool credit for not purchasing a long-term parking permit; free carpools and vanpools, along with reserved parking for carpool vehicles; Zipcar driving credit of up to $102 per year; free folding bicycle rental for 1 week along with subsidized purchase of folding bicycles; and the opportunity to win other prizes through regular drawings.

Hypothetical Uses of Emerging Technologies and Data

- ML to optimize traffic flow incentives and monetary awards.
- Integration with the application Waze so that incentives and awards can reflect real-time events.

For more information, see https://prabhakargroup.stanford.edu/research/societal-networks/capri-project.

CHARM PROGRAM IN THE NETHERLANDS

ATDM Approach: ATM.

Emerging Technologies and Data Currently in Use: ML algorithms for incident prediction, in-car sensor data (e.g., speed, use of brakes, use of lights, use of wipers, steering wheel position, headway to the next vehicle), "autopilot" for traffic controllers, data fusion algorithms (i.e., to integrate floating car data, closed circuit television [CCTV], Twitter, applications, rainfall radars, and emergency services reports), Talking Traffic (i.e., organized use of clustered data and communications), and ability of road users to access traffic management center data.(34)

CHARM is the program that will help Rijkswaterstaat to shape traffic management in the right way in the future. It is a smart platform which will be used in the traffic centers and along the road by on duty road inspectors and officers.

The CHARM program (2015 through 2020) is a collaboration project between the Ministry of Infrastructure and Water Management (Rijkswaterstaat in Dutch) and Highways England. The objective is to migrate to an advanced traffic management system (ATMS), supporting all required business processes for network management in an integrated way. The expected outcome of CHARM is an open, modular, high-level information and communications technology architecture for TMCs. It is based on the standardization of TMC requirements by the United Kingdom, the Netherlands, and Belgium ((CHARM Pre-Commercial Procurement [PCP] Common Traffic Management Model Highways Agency, Rijkswaterstaat and Mobiliteit en Openbare Werken, 2019). In addition, CHARM's goal is to achieve an ATMS that is integrated, flexible, scalable, and has the ability to easily incorporate new or additional (third-party) modules (CHARM PCP Project Publishable Summary period 3, 2019). It is expected that the majority of existing applications will be replaced. New modules that will specifically be developed for this architecture will offer significant improvement of traffic management services. The current Rijkswaterstaat scope of the CHARM program covers all regional road traffic control centers and traffic centers in the Netherlands and the approximately 300 future users, such as road traffic controllers, road inspectors, law enforcement entities, and operational traffic experts (Rijkswaterstaat, 2019).

Talking Traffic is a collaboration between the Dutch Ministry of Infrastructure and the Environment, 60 regional and local authorities, and national and international private companies. These partners are working together to accelerate development and deployment with regard to retrieving and organizing traffic light data (cluster 1); to process and enrich the distribution of a wide variety of data and convert this into real-time and made-to-measure data sets and information (cluster 2), and to provide this information to a wide variety of road users (cluster 3) though their smartphones, personal navigation devices, and in-car systems.(16, 41)

THE PRE-COMMERCIAL PROCUREMENT PROJECT

The CHARM PCP project[6] was the first step in the CHARM program. This project, which started in 2013 and ended in August 2017, challenged the private sector to develop innovative traffic management modules that fit within a new, flexible, common architecture for TMCs. Each new module is expected to significantly improve traffic management performance. The CHARM PCP resulted in the development of prototypes in the following challenge areas:

The CHARM PCP project is in many ways an excellent example for future PCPs.

- Advanced distributed network management.
- Detection and prediction of incidents.
- Support of cooperative ITS functions (in-car systems).

In September 2017, the European commission judged the results of the CHARM project to be excellent.

It is expected that the developed innovative modules shown in table 7 will be integrated into a new ATMS traffic management platform. Integration of these modules into the ATMS system will result in an integral and comprehensive TMC with innovative functionalities, all in one platform.

Table 7. Modules for each challenge area.

Challenge Areas	Module	Function
Advanced Distributed Network Management	Right on track.	Provide road users with optimal routes.
	Inspiration in mining.	Servicing real-time traffic demand via automated traffic controllers.
	Autopilot.	Automatic pilot for traffic controllers.
Detection and Prediction of Incidents	Advanced data patrolling.	Real-time information on traffic demand and network condition.
	Learning algorithms.	Detect and predict all types of incidents.
Support of Cooperative Intelligent Transportation System Functions	Connected cars.	Autonomous traffic flow management.
	In-car application.	Real-time traffic conditions.
	Cooperative data.	Establish communication between a co-operative network of vehicles.

More information on the details of each module can be found in the CHARM PCP in Phase 2 publication.[7]

6 The three-phase PCP involved the collaboration of Dutch, Flemish, and English partners (public sector): Vlaamse Departement voor Mobiliteit en Openbare Werken, Rijksdienst voor Ondernemend Nederland, and Innovate United Kingdom.

7 https://cordis.europa.eu/docs/projects/cnect/2/318722/080/deliverables/001-NewsletterCHARMPCPinphase2editionJune2015.pdf

THE CHARM ADVANCED TRAFFIC MANAGEMENT SYSTEM PROJECT

Smart traffic management is essential for the proper functioning of future road technologies such as smart vehicles and smart infrastructure. CHARM is the solution for providing smart traffic centers to cater to future road needs.

The new traffic management links approximately 30 systems to one national platform. For Rijkswaterstaat, the platform will run in the Government Data Center to which all road traffic control centers are connected (Rijkswaterstaat., 2019). By linking with ATMS software, regional and national stakeholders will have a more uniform collaboration with Rijkswaterstaat. The scope of the CHARM program consists of all core functionalities used to support services and traffic management processes that are delivered from TMCs. This includes the interfaces to roadside equipment from/of internal and external users. The ATMS software package will support the business processes of both Highways England and Rijkswaterstaat, consisting of (Rijkswaterstaat. 2019):

- Information provision.
- Dynamic traffic management.
- Incident management.
- Resource management.
- Event planning.
- Contact management.

APPENDIX: REFERENCES

All documents used in, and to support, this report are listed below.

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